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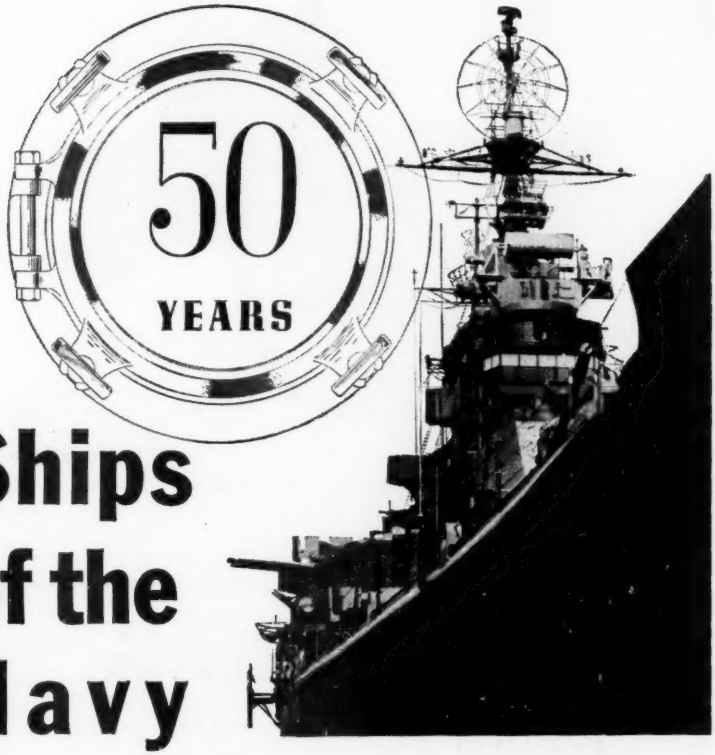

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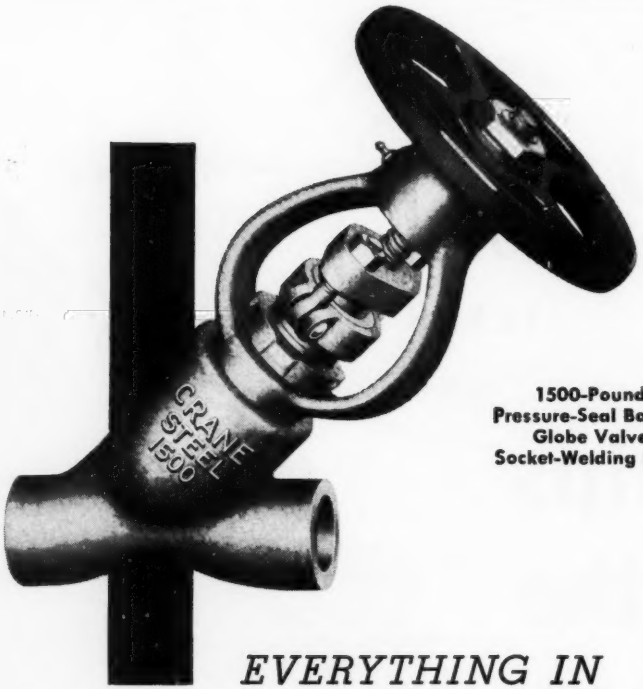

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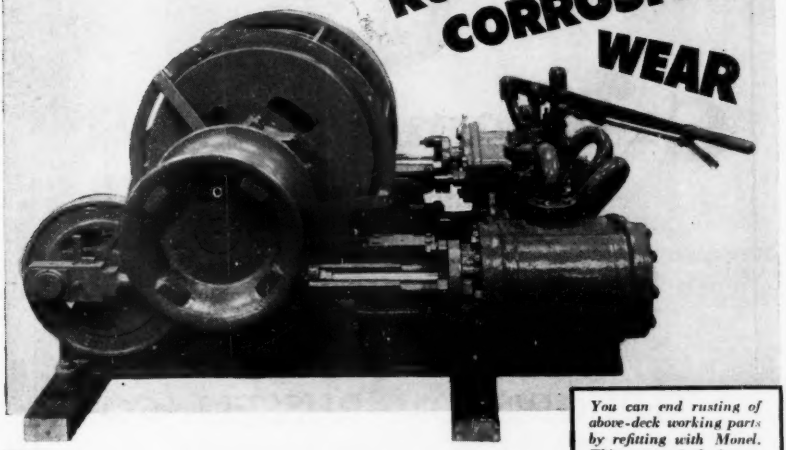

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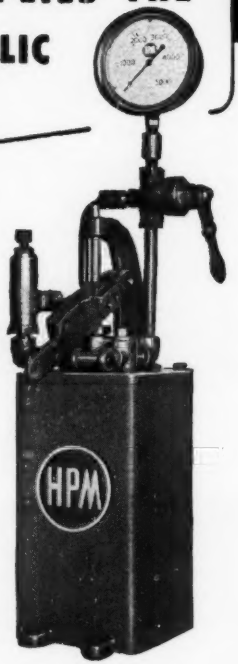

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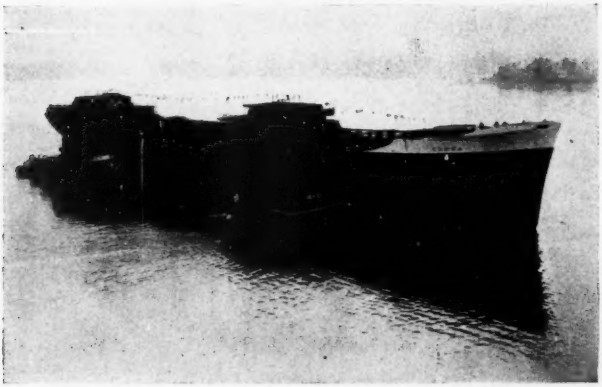

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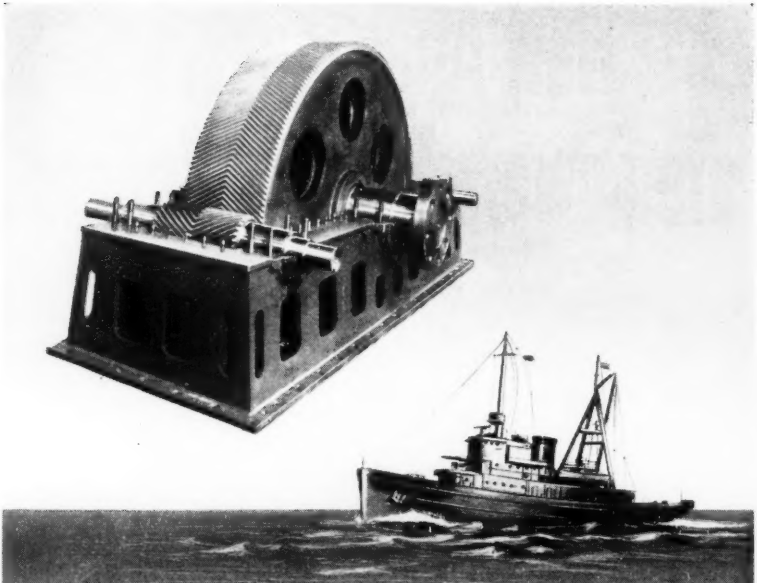

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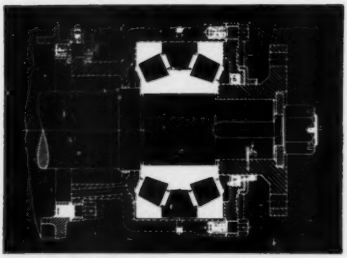

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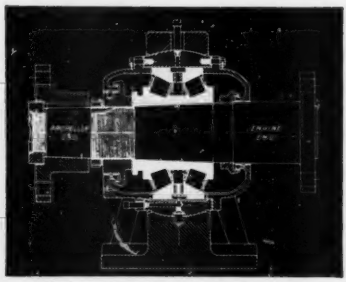
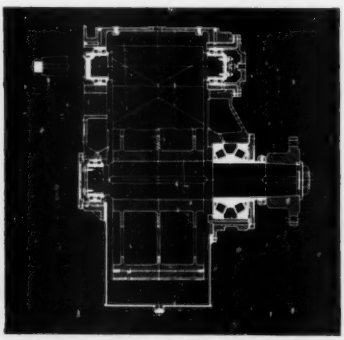


Timken bearing separate thrust block for use between engine and propeller shaft.



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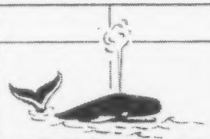
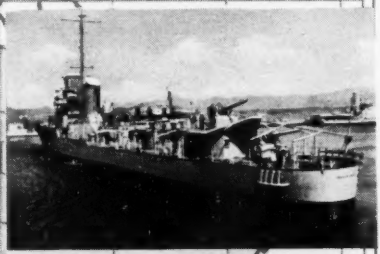
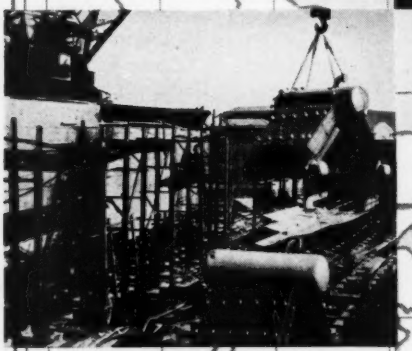


C. T. Amazonas after launching at Rio de Janeiro.





B&W boiler pressure parts being hoisted into C. T. Amazonas

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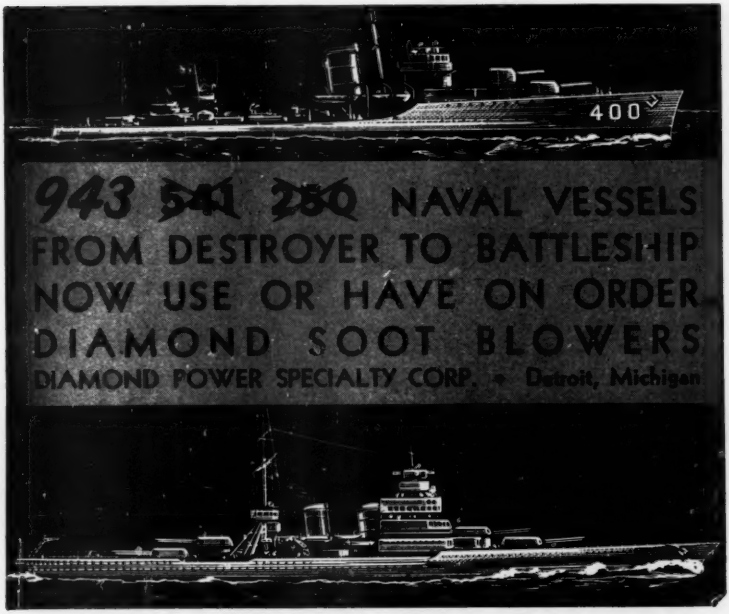
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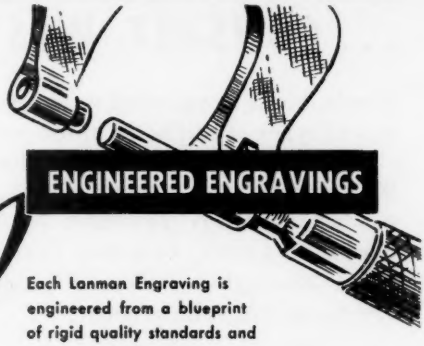

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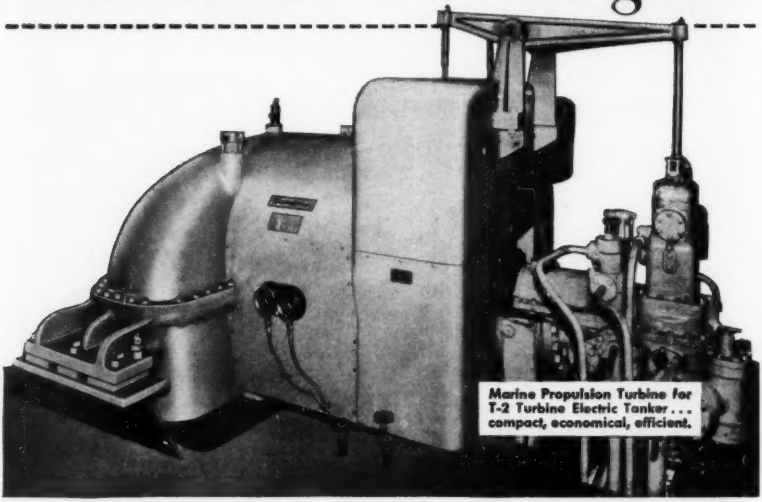

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IN WASHINGTON, D. C.

ON

FRIDAY, 28 APRIL, 1950

MR. DAVID SARNOFF

CHAIRMAN OF THE BOARD

RADIO CORPORATION OF AMERICA

WILL BE

THE PRINCIPAL SPEAKER

Official U.S. Navy Photograph

REAR ADMIRAL FREDERICK E. HAEBERLE, U.S. Navy, President of the Society, 1950.

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JOURNAL

OF

THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

VOL. 62. FEBRUARY 1950. No. 1

Statements contained in articles herein are the private opinions and assertions of the writers and should therefore not be construed as reflecting the views of The American Society of Naval Engineers, Inc., or of any other organization with which such writers are affiliated.

The Society as a body is not responsible for statements made by individual members

COUNCIL OF THE SOCIETY

(Under whose supervision this number is published).

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Captain J. E. HAMILTON, U.S.N., Secretary-Treasurer

SECRETARY'S NOTES

1949 ELECTIONS

The Officers of the Society who will serve during 1950 as a result of the 1949 election and carryovers are:

President: Rear Admiral F. E. Haeberle, U.S.N.

Secretary-Treasurer: Captain J. E. Hamilton, U.S.N.

Council: Regular Navy: Captain Homer Ambrose, U.S.N.
Captain T. T. Dantzler, U.S.N.
Rear Admiral Louis Dreller, U.S.N.
Captain C. M. Tooke, U.S.N.

Naval Reserve: Captain W. W. Tann, U.S.N.R.
Comdr. Nicholas Tiedeman, U.S.N.R.

Coast Guard: Captain R. A. Smyth, U.S.C.G.

Civilian: Mr. Francis H. Engel
Mr. R. M. Wilson

Secretary's Notes

The sincere thanks of the Society are due to the retiring president, Rear Admiral T. A. Solberg, U.S.N., and to those members of the Council whose terms expired with 1949, namely:

Mr. M. Douglas Gibson, Jr.

Captain P. D. Gold, U.S.N.

Captain G. F. Hicks, U.S.C.G.

Rear Admiral T. C. Lonnquest, U.S.N.

Captain W. N. Mansfield, U.S.N.R.

As a result of the balloting on three proposed changes to the by-laws, all were adopted. These changes and their effects are being considered by the Council. Rules for the establishment of Life Memberships and of local chapters will probably be adopted in time for promulgation in the May 1950 issue of the Journal.

In the meantime all members who are looking forward to buying life memberships are advised that any annual dues paid for the year in which application is made for Life Memberships will be credited to the cost of the Life Membership.

Annual Banquet

Forms for application for the Society's Annual Banquet will be placed in the mail very soon. The banquet, as has been announced previously, will be held on Friday, 28 April 1950. The locale will be the Statler Hotel, Washington, D. C., with arrangements very similar to those which contributed to the very successful 1949 banquet.

As in the past one non-member guest will be permitted for each member unless applications exceed the hotel's capacity. In that case non-members, to the greatest number possible, will be permitted as guests of those members whose applications are first received. The cost will be the same as in 1949, namely: $10.00 for members and $12.50 for non-members.

The Society has been signally honored by the acceptance by Mr. David Sarnoff of an invitation to be the principal speaker at the banquet. Mr. Sarnoff, Chairman of the Board of the Radio Corporation of America, needs no introduction to Naval Engineers.

SECRETARY'S NOTES

Increase in Dues

Beginning with 1950, the annual dues of the Society have been raised to $7.50. All new members are being accepted at that rate. Old members will note the increased rate in the bills which have been mailed.

VOLUME 62

The current issue of the JOURNAL is the first number of a new Volume 62. It marks the beginning of the 62nd consecutive year of publication. As has been pointed out repeatedly in the past, the quality of the JOURNAL is determined almost entirely by the quality of the original articles which are submitted for publication. All members and friends of the Society are urged to offer the JOURNAL timely articles which will make their knowledge and experience available to all readers.

MEMBERSHIP AND ADVERTISING

The Society does not intend to make a formal drive during 1950 for either members or for new advertisers in the JOURNAL. However, moderate accretion in both will tend to keep the Society strong. All members are urged to encourage eligible candidates to apply for membership and to point out to prospective advertisers the select coverage and low advertising rates which the JOURNAL offers.

JOINT 1949-1950 COUNCIL MEETING

Sitting: Mr. Fessenden, Clerk; Rear Adm. Dreller, 1950-51 Council; Rear Adm. Haeberle, 1950 President; Rear Adm. Solberg, 1949 President; Capt. Hamilton, Sec.-Treas.; Mr. Engel, 1950-51 Council.

Standing: Comdr. Jones, Asst. Sec.-Treas.; Capt. Tann, 1950-51 Council; Mr. Gibson, 1948-49 Council; Capt. Dantzler, 1949-50 Council; Capt. Mansfield, 1948-49 Council; Capt. Gold, 1948-49 Council; Capt. Tooke, 1950-51 Council; Com. Tiedeman, 1949-50 Council; Capt. Smyth, 1950-51 Council.

Absent: Rear Adm. Lonnquest, 1948-49 Council; Mr. Wilson, 1949-50 Council; Capt. Ambrose, 1949-50 Council; Capt. Hicks, 1948-49 Council.

Capt. Mansfield, 1948-49 Council; Capt. Gold, 1948-49 Council; Capt. Tooke, 1950-51 Council; Com. Tiedeman, 1949-50 Council; Capt. Smyth, 1950-51 Council.
Absent: Rear Adm. Lonnquest, 1948-49 Council; Mr. Wilson, 1949-50 Council; Capt. Ambrose, 1949-50 Council; Capt. Hicks, 1948-49 Council.

PART ONE

ORIGINAL ARTICLES

The articles which the Editor, acting under the supervision of the Council, has accepted for publication in Part One are the original works of the authors.

They are offered in furtherance of the Society's raison d'etre: to further the advancement of naval engineering. Discussion of any article is invited for publication in a subsequent issue.

Permission to reprint is freely granted on condition that *full acknowledgment is given* to the author and to the JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS.

All articles which have been written by naval personnel and are published herein carry the personal view of the authors and, unless specifically so stated, do not express the official views of the Navy Department.

Official U. S. Navy Photograph.

Pearl Harbor Navy Yard on December 7, 1941. Little Industrial Mobilization Planning Preceded This Date.

Pearl Harbor Navy Yard on December 7, 1941. Little Industrial Mobilization Planning Preceded This Date.

INDUSTRIAL MOBILIZATION PLANNING

REAR ADMIRAL D. H. CLARK, U. S. NAVY

THE AUTHOR

ADMIRAL CLARK is the Chief of the Bureau of Ships of the Department of the Navy, having been appointed to that position by President Truman, February 1st, 1949. He graduated from the U. S. Naval Academy in 1918; was awarded a MS degree from Columbia University in 1925. Prior to his present assignment, Admiral Clark served as Commander, U. S. Naval Shipyard, Portsmouth, Virginia and Commanding Officer and Director of the Naval Engineering Experiment Station, Annapolis, Maryland. He was Fleet Engineer Officer on the Staff of the Commander in Chief of the Pacific Fleet when the hostilities commenced for the United States in World War II. He returned to become Planning Officer of the Navy Yard, Boston, Massachusetts in the autumn of 1943.

Note: *The author accepted no compensation for this article.*

September 1945 found the United States putting aside its wartime gear at the close of the most far-flung, devastating and costly war in all history. Hopes for a long era of peace were high. Although initially recognized as such by only a few, the United States emerged from the conflict as the leader among democratic nations and the guardian of freedom in the world.

World War II had been under way 27 months when we entered the conflict. Our relative unpreparedness and unreadiness for war took its toll of precious lives and inflicted a costly material burden on our nation. During these 27 months we did raise our material output tremendously, but, in our haste we had no opportunity to calmly and objectively develop those measures of over-all planning so necessary to the prosecution of total war. Consequently, ultimate victory was ours only at the cost of waste in lives, material, time and effort.

The end of the war brought about a demobilization of unprecedented magnitude effected at reckless speed. Everyone sought to forget the war and return to peaceful pursuits. The wartime Armies and Armadas rapidly became impotent as all our people were united with the desire that war should not overtake us again. Few gave thought as to how that desire might be achieved. Those few who did think it through,

recognized that it was essential that our security be planned for, and that the planning be so devised that during the hoped for years of peace we would neither overburden the business effort of the nation, nor require excessive expenditures from the Treasury of the United States. To this end, plans were evolved; initially separate plans laid down by the three (3) military departments, and later, joint plans coordinated cooperatively.

If costly waste is not to occur again, it is necessary that present day mobilization planning be examined in the light of experience, and such examination is the purpose of this paper.

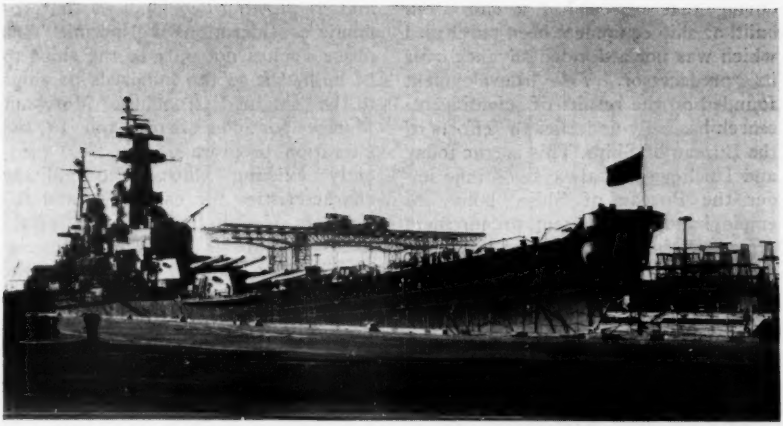
In general the things which must be planned are the steps to be taken to shift the United States of America from a peacetime footing to a wartime footing which will provide positively for the defense of our Country. This mobilization planning is an extremely broad subject, embracing, in its final aspects, the economy, the material and the human elements of our entire population and directly affecting every individual in our population of 150,000,000. I do not propose to discuss the whole broad subject. I should like, however, to discuss that portion of it with which I am officially connected and concerned — *INDUSTRIAL* MOBILIZATION PLANNING.

The Munitions Board, which was established by the National Defense Act of 1947, was the first activity in the new Defense Establishment to emerge from unification as a going concern. The reason for this was that the Army-Navy Munitions Board had existed as a Joint enterprise for many years. It was manned by service personnel who had just come through World War II and who were thoroughly acquainted with the problems and controls of industry in World War II. They, as much as any group, were determined that "it should not happen again". It is a fact that by the Spring of 1948 the Munitions Board had promulgated some of the elements of a broad Industrial Mobilization Plan which had been initiated by the Army-Navy Munitions Board. I intend to discuss the aspects of this plan which are pertinent to the Bureau of Ships of the Department of the Navy.

At the peak during World War II, the Navy was operating about 8400 ships ranging in size from motor torpedo boats to the *Missouri* type battleship, not including several thousand service craft such as barges, lighters and small tugs, nor several tens of thousands of small landing craft and other boats. It appeared to some that with this tremendous number of ships our sole job would be to hold on to them, and thus eliminate the need for building any more for or during another emergency. However, there are many considerations to a matter of this kind. After the war, many vessels were returned to their former owners. Some sorely needed craft were transferred to other countries. Then economic considerations required the elimination of the ships whose design and condition did not warrant the expense of trying to keep them. By these processes the Navy was reduced to a total of about 2700 vessels, representing the best of the World War II fleets.

Planning for any future emergency is very fluid and at no time is it possible to sit down and say that "the job is done". At the moment it appears that our plans for any war emergency which may come will require that the Navy operate somewhat fewer ships than were required to win World War II but considerably more than the 2700 which are now on hand.

To make up the deficiency, it is probable that the Merchant Marine, active and reserve, can provide a great many vessels which can be adapted to Navy requirements. This will still leave a sizeable balance to be newly constructed.



Official U. S. Navy Photograph.

U. S. S. *IOWA*—in San Francisco Naval Shipyard

The 2700 ships on hand are today roughly divided—about 25% in the active fleet and the remainder in the reserve fleet in "moth balls". The percentage of active ships must vary with strategic requirements and budget allowances. Every effort is made to keep the active fleet ships fully modern and in a material condition which make them continually ready for instant combat service, in so far as appropriation of funds permits. This nucleus active fleet will have to be expanded many times to meet the threat of another war. The Bureau of Ships' Mobilization Planning task is to be prepared to undertake and accomplish this expansion.

To accomplish its mobilization task, the Bureau of Ships' effort is divided into programs as follows:

A—Navy Ship Programs
- 1—Ship repair and maintenance (Active Fleet)
- 2—Ship activation (Adding reserve ships to the Active Fleet)
- 3—Ship alterations (Modernizing existing ships)
- 4—Ship conversion (Changing merchant types to Naval types)
- 5—Shipbuilding (new construction)

B—Auxiliary Program
- 1—Rearming of Merchant Ships

C—Supporting Programs
- 1—Outfitting of Advanced Bases
- 2—Shore electronics facilities
- 3—Expansion of industrial facilities
- 4—New industrial facilities.

The supporting and auxiliary programs which I have listed have to be, and are provided for in our planning just as carefully as the ship programs are. However, since they flow from the ship programs and from the strategic plans which result in the deployment of ships, I shall devote this paper to the ship programs.

"Research and Development" is not listed as one of our Mobilization Planning Programs. The Bureau of Ships, as the successor to the Bureaus of Engineering and of Construction and Repair, has an industrial history of more than 100 years. Rarely, if ever,

during that period has a ship been built, or ship equipment been purchased which was not a decided advance over its predecessor. *True* development founded on the results of scientific research basically underlies the efforts of the Bureau of Ships. This is true today and I believe will always continue under the Bureau of Ships' policy of employing in its current procurement programs the vast resources of scientific and engineering brains and skill of industrial and research organizations available in the United States.

In planning our mobilization effort, the individual requirements of each ship must be considered. These requirements will vary with circumstances. Figure 1 illustrates hypothetical schedules for several typical ships. During each of the periods shown some material will be required which must be *designed* and *manufactured* before it can be made available to the ship. Until that material whether it be a turbine, a radar set, or a pair of binoculars, is available to, and a part of an operable ship, it is not effective. A radar set installed in a ship in a combat zone might decide an action. In a crate in a warehouse or boxcar, it can not affect the outcome of an engagement.

The segments of Industrial Mobilization Planning for ship purposes may be simply stated as:

A—Design
B—Bills of Material
C—Facilities

DESIGN

There are three salient steps of ship design—the first of these is military characteristics which are furnished by the strategic planners working, in advance, for the officers who will have commands in combat areas. These military characteristics are necessarily a compromise between what the officers charged with determining the characteristics would like to have and what the *current* level of scientific research and engineering development and economic considerations will permit. This phase applies not only to the ships to be built, but to the hundreds of ships to be obtained from the Merchant Marine for conversion, and to the alteration program of the 2700 presently existing ships. The military characteristics for each type and the numbers of ships of each type, establishes the basis of the Industrial Mobilization Planning work load of the Bureau of Ships.

The second design step is the translation of the military characteristics into contract plans, that is: plans which are specific enough to permit a shipbuilder to know what is wanted and to protect the Government's interest while, at the same time, general enough to permit full play of ingenuity, knowledge and imagination of those who will develop working plans. Naturally, the contract plans for a ship to be newly built are quite different from those for the conversion of one already existing. In some instances contract plans are not required for existing ships which are to be altered or modified, but specific instructions must be devised to cover the alterations.

The third design step is the working plans. These include the detailed drawings and specifications which are given to shops in the shipyard where the work is to be done, plus those which go into the shops of the manufacturers who are making or building things to go into the ship. Even the simplest small ship involves hundreds of drawings. For a large ship, this involves millions of drawings, bills of material and schedules which govern the production of items in hundreds of factories spread all over the United States.

Our peacetime procurement though it involves all of these design stages, is limited in quantity. Our current work is hardly a drop in the bucket, measured in dollars. Mobilization requires many-fold increases over cur-

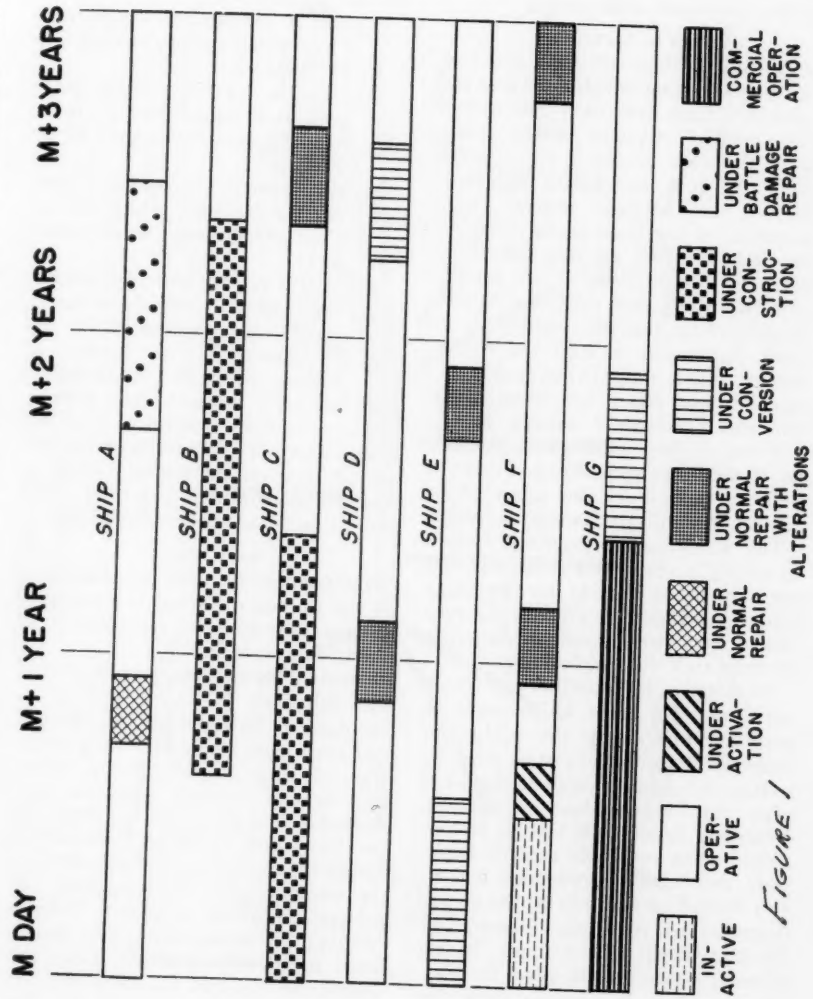

M DAY
M+1 YEAR
M+2 YEARS
M+3YEARS
SHIP A
SHIP B
SHIP C
SHIP D
SHIP E
SHIP F
SHIP G
IN-ACTIVE
OPER-ATIVE
UNDER ACTIVA-TION
UNDER NORMAL REPAIR
UNDER NORMAL REPAIR WITH ALTERATIONS
UNDER CON-VERSION
UNDER CON-STRUC-TION
UNDER BATTLE DAMAGE REPAIR
COM-MERCIAL OPER-ATION

FIGURE 1

rent rates. The gap between current levels, and the industrial effort required on mobilization demands careful planning, and all planning, to be worthwhile, must start with design.

BILLS OF MATERIAL

A "Bill of Material" for a ship is a list of everything which goes into the final ship. Each item listed is described, the number required stated along with the date required for installation. All such items must be transcribed into purchase orders. Those purchase orders must reach manufacturers before they are in a position to place further purchase orders for the material which they need, and to hire labor, and to study the capabilities of their plants and to start the wheels turning. In a multi-billion dollar industrial war effort for ships, these purchase orders will number in the millions as they reach down through all levels of subcontracting. Figure 2 indicates a few of the items to be found in the Bills of Material for ships.

One of the most important factors in placing purchase orders for material for ships is to provide for necessary lead time. Figure 3 presents in very simple form some aspects of lead time for materials for shipbuilding.

Manifestly, in peacetime we could not employ the force which would be necessary to plan for the millions of items which would have to be procured so that the suppliers could be furnished with full information in advance. Necessary details will have to be furnished when and if we actually implement mobilization production and we will depend very largely on the normal processes of American industry for handling most of the items. In the planning phase we will select for planning purchase in advance those few items which will provide the greatest benefits through educating the supplier in procedures and reducing lead times. The criteria used in these selections are based on knowledge derived from experience. To determine whether the item is one which, through planning, is susceptible to reduction of lead time, the following factors, among others must be considered:

(a) Has it complicated design features which can be worked out in advance?
(b) Does it contain critical components or material which, to be available, must be planned for in advance?
(c) Will it require expansion of productive facilities, which can be sited and designed in advance? and
(d) Will it require extensive retooling to produce and the procurement of the new tools which can be planned for or, funds permitting, stockpiled in advance?

Once we have selected these critical items, it is then necessary to carry Design and Bill of Material efforts far enough to cover the selected items so that the specifications and total numbers of each one can be determined.

FACILITIES

The facilities required for production of the Bureau of Ships' requirements fall naturally into two categories—

1st—shipyards and

2nd—manufacturing plants other than shipyards.

Shipyards have the special feature that they must be located on a water front. During World War II there were several hundred operating shipyards building and repairing ships for the Navy and Maritime Commission. Today the number is less than 20% of the wartime peak. At that peak, the private shipyards employed 644,000 workers on shipbuilding and repair work for the Navy alone; today the number so engaged on Navy work is less than 6,000, about 9/10 of 1%. The task of planning the expansion in one single industry which mobilization would demand without upsetting other industries, is a real task. Its imple-

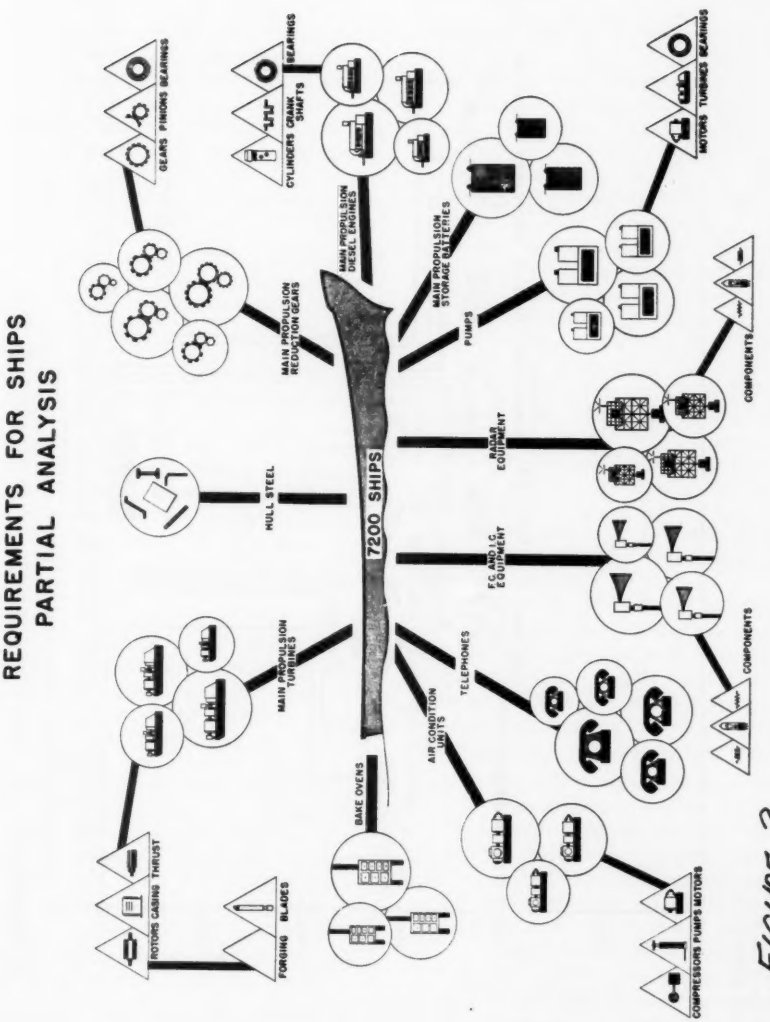

REQUIREMENTS FOR SHIPS
PARTIAL ANALYSIS
7200 SHIPS
ROTORS CASING THRUST
FORGING BLADES
MAIN PROPULSION TURBINES
BAKE OVENS
AIR CONDITION UNITS
TELEPHONES
COMPRESSORS PUMPS MOTORS
HULL STEEL
MAIN PROPULSION REDUCTION GEARS
GEARS PINIONS BEARINGS
MAIN PROPULSION DIESEL ENGINES
CYLINDERS CRANK SHAFTS BEARINGS
MAIN PROPULSION STORAGE BATTERIES
PUMPS
RADAR EQUIPMENT
FC AND I.C. EQUIPMENT
COMPONENTS
MOTORS TURBINES BEARINGS
COMPONENTS

FIGURE 2

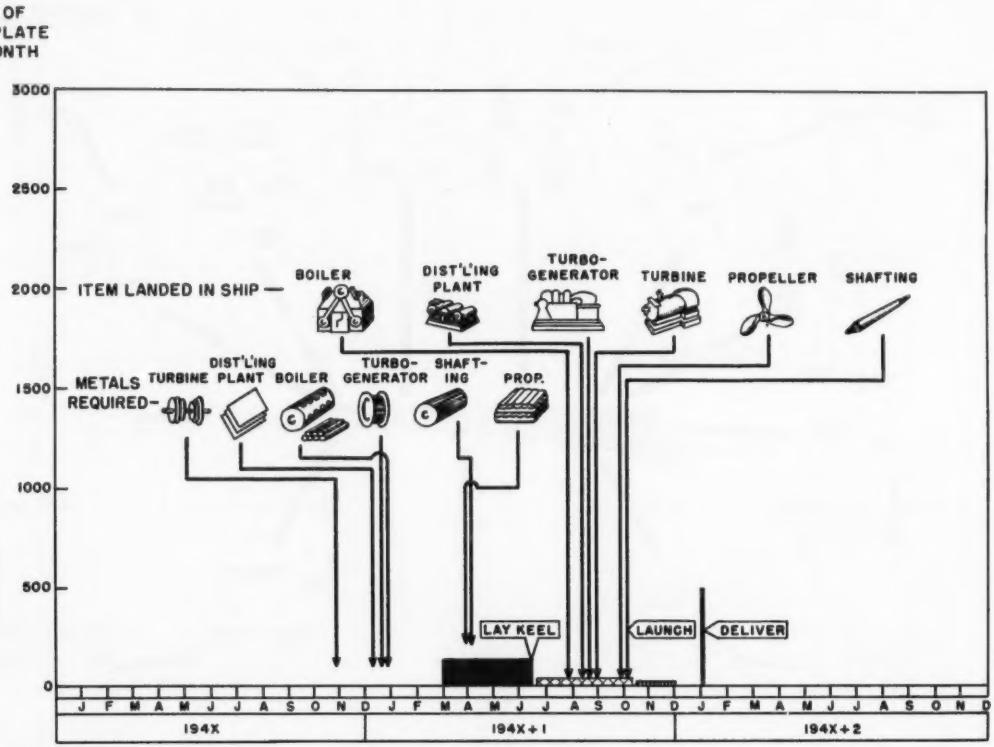


FIGURE 3 DESTROYER ESCORT (DE 74 TURBO-ELECTRIC)

mentation, if we are forced to mobilize, will involve Herculean efforts.

Some of the shipyards which were built during World War II are still available in various stages of repair. As time goes on this number of facilities diminishes, deterioration increases, and readiness for resuming operations declines. It will be necessary to construct additional shipyards on the best sites available. This problem, of course, becomes aggravated if planning assumes that enemy inflicted damage will affect the shipyard areas.

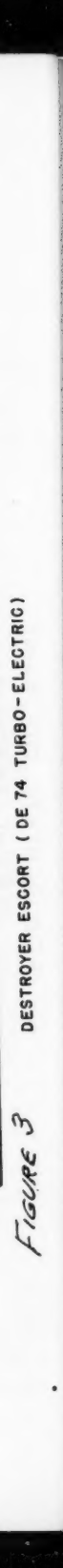
In those manufacturing plants other than shipyards, the problem is quite different. It is probable that not a great deal more labor will be required in the contributory industries than is now employed for manufacturing their commercial products. In these industries, as far as the Bureau of Ships is concerned, the major task will be to supply management with design and quantity information so that the transition from the production of commercial products to the production of ship components and material upon mobilization, can be undertaken.

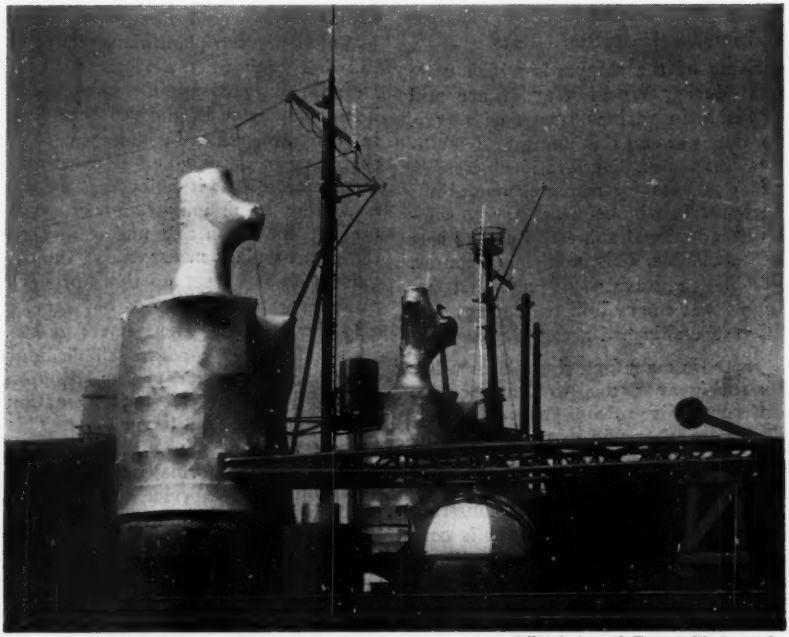
The Munitions Board Plan, which I mentioned earlier, has given the Services procedures for acquainting manufacturers with the information they require to make the necessary conversions. These procedures are designed to make the transition of industry from peace to war very smooth and simple. As indicated before, full implementation can not be expected because of the sheer volume of the work, but if the Munitions Board Annex 47 procedure is completed properly, much will have been accomplished and that much less will remain to be done if and when M-Day comes.

Under the Munitions Board Plan, described in Annex 47, formal procedures are set up for: (a) determining roughly what each manufacturing plant is capable of doing, and what its management would like to do; then (b) advising that plant management as to what each of the Department of Defense Bureaus and Services would like to buy from it, and (c) receiving, in reply, acceptance by management of the plant of as much of the procurement schedules as it believes it can and is willing to assimilate. In order to prevent confusion and uncertainty on the part of plant management, the organization is so set up that for each plant the representative of one service acts for the entire Department of Defense and solely conducts all dealings with plant management in mobilization planning, and their implementation should mobilization be ordered. This representative acts for all Services and Branches and is normally appointed by a branch of the Service which in the opinion of the Munitions Board has the predominant interest in the plant. The Department of Defense representative is known as the Armed Services Procurement Planning Officer and, as stated, all claimants in the Department of Defense act through him in dealing with management.

The plan is devised to put the United States in the best possible position for mobilizing for war. The cost of this planning is small, yet it represents prospective purchases aggregating many billions of dollars. It operates to improve our position in two ways.

First—in the Department of Defense, the strategic planning is put on a solid foundation. The Services are in a position to tell the strategic commanders what they can expect to have *because* industry has said it could produce at that rate and in those quantities. This should permit strategic operations to be planned and implemented with a great deal more smoothness and certainty than has characterized them in the past.





Official Armed Forces Photograph.

Like two ogres, these plastic envelopes stand guard over inactivated submarine tenders of the Pacific Reserve Fleet in the Mare Island Naval Shipyard, Vallejo, California, ready and waiting for duty if called.

Second—the management of each industrial plant having been advised what it will be asked to produce, if we mobilize, is in a position to (in fact it is expected to) do a modicum of real production engineering and to take the preliminary steps toward arranging things so that its wartime production will get into swing and reach a peak as soon as possible. Merely by clearing the way now so that firm orders may be placed, with the preliminaries already undertaken, we can reduce productive lead time by many months.

As ancillary step to the Annex 47 procedure, the Department of Defense has limited amounts of funds for carrying out certain Industry Preparedness Measures which should be undertaken after the formal procedure has been completed and has disclosed what measures have promise of productive results, that is: low cost effort *now* will produce reduction of lead time *after M-Day* when time will be at a premium. These Industry Preparedness Measures are of several types. The principal ones are:

A—*Exploratory Studies* wherein the known sources of production of any material or product are insufficient and it is necessary to conduct a detailed engineering study to find additional sources or the means of increasing the productivity of the known sources.

B—*Production Studies*—detailed en-

gineering study made to design a production line adequate for the required production; or a laboratory model is redesigned for mass production; or other similar measures are taken relative to a particular facility or a particular product so that its production may be expedited.

C—*Educational Orders* wherein a manufacturer, who has never had experience with some required product, is given a contract to produce a limited quantity primarily for his own familiarization and

D—*Pilot Runs* wherein a product which has never been produced beyond the laboratory or prototype stage is covered by a contract with the manufacturer so that he can set up production line methods and actually test them by turning out a limited number of products.

The Industry Preparedness Measures just mentioned will normally be paid for by the Government although there are cases on record where manufacturers have absorbed a generous portion of the cost. Other measures which are described under the formal Annex 47 procedure are intended to be accomplished by the manufacturer at his own expense. The justification for this expenditure by manufacturers has been based largely on patriotic grounds. Actually, the moderate expenditure which such planning requires is of self interest, and in the nature of market research, and can only tend to improve the economic position of a company which does it in the event mobilization becomes necessary. These measures will reduce the length of time during which industry has to remain mobilized for war and will facilitate the transition back to peace.

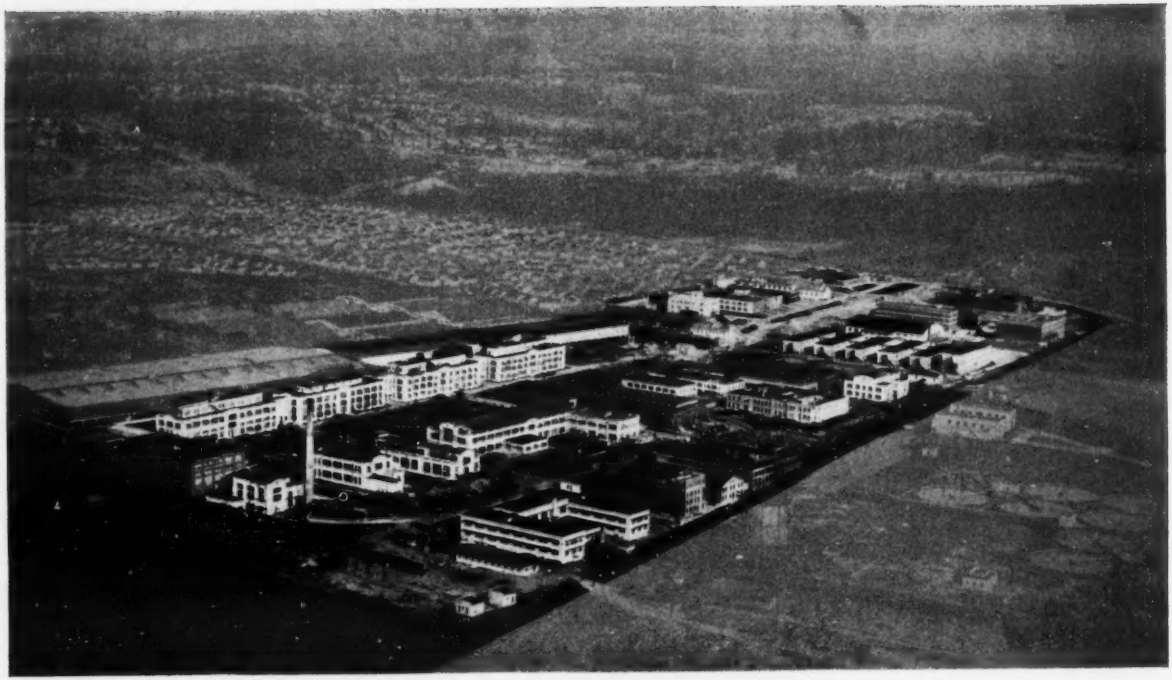
Accompanying Industrial Mobilization Planning as such, there are several concomitant operations under way in the material field. Although these are considered as more pertinent to current operations than to possible mobilization, their contribution to mobilization will be invaluable. The things which I have in mind, both under the guiding aegis of the Munitions Board, are:

(a) The Standardization Program, under which, to the maximum extent possible, a single standard and specification for functionally similar articles will be developed for use by all the Bureaus of the Navy, the Air Force and Services of the Army.

(b) The Cataloguing Program under which all articles used by any of the Bureaus or Services will be identified and catalogued and similar articles now bearing different Bureau or Service identifications will be brought together under a single catalogue number.

These programs are tremendous in their scope and will take some time to be fully accomplished. However, just as in Industrial Mobilization Planning, each little accomplishment which is truly a part of the final whole is just so much gained. Tremendous gains have been made.

War is just what General Sherman said it was. It is not pleasant to contemplate. Industrial Mobilization Planning is handicapped because it must be discussed and planned as if war was a possibility. Nevertheless *Industrial Mobilization Planning* carried on at a reasonable tempo; thoroughly understood by the Department of Defense, and by Industry; and recognized as necessary by the people of the United States, will do as much to prevent war by making a possible ambitious aggressor hesitate as any one thing which we can do.



NAVAL RESEARCH LABORATORY, ANACOSTIA, D. C.

NAVAL RESEARCH AND DEVELOPMENT IN WORLD WAR II

The Complete Story of the Co-ordination which was Developed During the War to Guide Naval Research and Development and to Keep it Pointed Toward the Goal of Winning

REAR ADMIRAL JULIUS A. FURER, U. S. N. (RETIRED)

THE AUTHOR

REAR ADMIRAL FURER graduated from the Naval Academy at the head of his class in 1901 and transferred to the Construction Corps in 1903. He was one of the pioneers in bringing Scientific Management into our Navy Yards. In 1915 he supervised the raising of the F-4 off Honolulu from a depth of 304 feet, a salvage record for depth which still stands. He invented the submersible pontoon for the final stage of the operation. Such pontoons have been used for all submarine salvage undertakings since then. His assignments have covered a great variety of duty both in administration and in engineering including tours of duty in the Philippines, Brazil and Europe. From December, 1941 until his retirement in 1945 he was Coordinator of Research and Development for the Navy Department.

I. THE PLANNING OF THE ORGANIZATION

1. INTRODUCTION

Since the end of the war, many books and articles have told the story of the contributions made by America's scientists to our victory over the Germans and the Japanese in 1945. As yet, however, little has been written about the role that the Services played in giving effect to the special talents that were so freely offered by the civilian scientists. Because of this blank in the record the belief exists in some quarters that the problem of harnessing science for war is simple and can again be solved easily, should the need arise. Not much has been told of the way in which the Services worked out their

part of the problem of collaboration, how opposition to an untried formula was overcome, and why, once the pattern of collaboration had been established, organized research and development proceeded at unprecedented speed to produce new weapons and effective countermeasures to the enemy's devices. It is the purpose of this article to describe briefly what the Navy did between 1939 and 1945 to bring about this result.

The problem of the Navy in this endeavor was essentially the same as that of the other Armed Services. It was certainly not always easy to harmonize the points of view of the scientist and of the man who makes the profession of arms his life work. Their backgrounds are in many respects very different. In normal times the scientist looks upon the world as friendly. He likes to take all mankind into his confidence as soon as he makes a discovery. He wants his inventions and discoveries put to use promptly, especially when they are replacing obsolete things. It is alien to his nature to work in channels. He has a natural human desire to receive credit from his colleagues and from the public for the fruits of his labor. By contrast, the professional military officer must think of the world as potentially hostile, even in times of peace. It is his job to plan for war whenever and wherever it may come. He cannot take the world into his confidence, for one of the fundamentals of military science is to withhold from the enemy information about plans, weapons, and resources. Working in guarded channels therefore becomes a habit. Strategy and tactics must be based on the use of the existing means of waging war, however much the professional officer may realize their shortcomings and however keenly he may desire improved weapons and techniques. This all makes for conservation in even the most forward looking individuals. For men with heavy responsibilities and little imagination, it makes for mistrust of the new because it is new.

The marvel is that these divergent points of view were resolved at all and that a fairly good working partnership between the Armed Services and civilian scientists was achieved at the very beginning of the war.

2. SCIENCE IN THE AXIS WAR EFFORT

A brief review of the use made of their scientists by Germany and Japan in World War II will provide a measuring stick of sorts for evaluating our own achievements. Here the answer is simple: Effective liaison between science and the Armed Forces was never established in the Axis countries. This accounts largely for the fact that scientists did not contribute so effectively to the war effort in those countries as they did in the United States and in Great Britain. There is ample evidence from captured documents and from statements of those in position to know that the failure should not be charged to the scientists but to the political and military leaders of the Axis countries. It certainly cannot be laid to a low level of professional competence on the part of Axis scientists. As evidence of the ability of the relatively few German scientists and engineers who were integrated with the war machine are such achievements as the V bombs, the Mark XXI submarine, and major advances in aeronautics. Fortunately for the United Nations, these developments came too late to affect the outcome of the war.

It appears that Hitler and his military advisers were convinced of Germany's ability to win the war quickly with the improved weapons that had been developed during the peace period. Had this been a correct estimate of the situation, Germany would have needed no special organization of scientists for the development of new weapons during the war. It was reasoned, on this assumption, that the older scientists in university laboratories could be left to their peacetime

researches, in the expectation that the fruits of their work might be of value after the war in meeting international industrial competition and in the reconversion of Germany's own economy. Following this line of thinking, it was further believed that the younger scientists would need exemption from military duty no more than other educated men in their age groups. The error of this policy was acknowledged in 1943 by returning several thousand scientists from the Armed Forces to the laboratories, but it was too late, even though thereafter all scientists were exempted from military service.

During the first four years of the war, such weapon research and development as was undertaken in Germany was done largely in the laboratories operated by the Armed Services and by the war industries. The effort was directed mainly at improving existing weapons. Fundamental research was greatly curtailed. For example, basic research on radar was stopped by Hitler's orders in 1940 and was not resumed until 1942.

These were errors stemming from the faulty premise of a short war, but an even greater error was made in extending authoritarian methods to the management of scientific research and development. The Armed Services attempted to tell the scientists what to invent without permitting them to learn at first hand the problems to be solved. The scientists were given specifications but no opportunity to collaborate with the Services that were to use the devices to be produced. Moreover, what was needed was often very different from what was specified. An official of a German electrical firm testified after the war that only one of their engineers had been permitted to examine in actual operation the best of the radar sets they had manufactured. Under Nazi regimentation there was no place for the unhindered flow of ideas from scientists which contributed so much to increasing the military strength of the United States and Great Britain.

Furthermore, the secrecy with which Germany had prepared for war had had the effect of limiting participation in these preparations to a relatively small number of scientists and engineers of unquestioned political "reliability." The purge of scientific men of liberal and international views, as well as those of Jewish origin, from university faculties, research institutions, and civil service positions, still further weakened the German scientific effort.

In 1942, by which time the hopes for a short war had faded, the German Government attempted to bring academic scientists into war research. In May of that year Professor Wilhelm Osenberg, of the Technische Hochschule at Hanover, was made head of a committee to review the availability of research personnel at German universities and other laboratories for work on problems of the German Navy. In January 1943 he became head of the Reichsforschungsrat, an agency somewhat similar to our own Office of Scientific Research and Development. The RFR, however, was handicapped by the fact that Nazi officialdom, both civil and military, never quite learned that smoothly intermeshing relations between the scientists and the Armed Forces were fully as important to rapid success in research as was scientific competence. At the time of the German surrender, Professor Osenberg stated that "Germany lost the war because of incomplete mobilization and utilization of scientific brains." There is nevertheless no question that German war research was prosecuted far more effectively during the last half of the war than during the first years, and that it achieved some notable successes.

Japan's organization of science for war was even more faulty than Germany's. Her laboratories were fewer in number but some of them compared favorably with the best research es-

tablishments of the Western countries. The Government laboratories seem to have attracted only second-rate men, but Japan had some civilian scientists of great ability who, under proper conditions, could have made important contributions to the war effort. It would appear that the Armed Services knew so little of methods of promoting research that they not only told the scientists in detail what to invent but also how to do it. Furthermore, the scientists were often kept in the dark as to the purpose which a proposed device was to serve. Sometimes the components of a research program were parceled out to a number of laboratories, with instructions that the whole would be assembled at an undisclosed establishment when the time was right. It is estimated that, by American standards, Japan's utilization of her academic scientists was only 10 per cent effective.

In general, then, the enemy failed most miserably to avail themselves of their scientific potential in making war.

3. PREWAR CIVILIAN SCIENTIFIC ORGANIZATIONS IN THE UNITED STATES

Before proceeding with the story of the organization set up by the Navy Department in World War II to provide effective relationships between civilian scientists and itself, it will be desirable to mention the principal civilian scientific organizations that existed outside of the Government before the war. All of these were called upon, in one capacity or another, to aid the Navy in its wartime research and development programs. Historically, however, their significance lies in the tradition they represent: the organization of scientific talent for the service of the Government.

The first organized effort to employ scientists in solving war problems was the establishment by Act of Congress of the National Academy of Sciences during a crisis of the Civil War in 1863. The Academy is a self-perpetuating body, independent of Government control, but is required by its charter, whenever called upon by any Department of the Government, to investigate, examine, and report upon any subject of science or art. Neither the Academy nor any of its members can receive compensation for this work beyond reimbursement for the expenses incurred in performing it. The Academy operates through committees or boards of experts, many of whom are not members of NAS. Membership is limited to the 450 leading scientists of the country. Because of its high standards for admission to membership and the fact that it receives no appropriations directly from Congress, it is free from political influences. Its reports and advice are accepted as impartial and authoritative.

In 1916, in order to provide more effective means of applying scientific knowledge to the solution of the problems submitted by Government Departments, the National Academy created the National Research Council as its agent for carrying out the requested work. This was intended to be only a wartime arrangement, but proved so satisfactory that it was made permanent after World War I. The National Research Council operates through divisions covering the various fields of science. In general, the membership of the divisions is made up of representatives of the principal national scientific and engineering societies or organizations in the fields concerned, of representatives of the Government appointed by the President on the nomination of the President of the Academy, and of distinguished members at large. The active work of the divisions is carried on by committees, either permanent or temporary, which are composed of men outstandingly qualified for the specific undertakings. In the spring of 1940 more than 1,100 individuals were actively engaged on NRC work for the Government.

Useful as its contributions had been

in World War I and great as were the services it was rendering to the war and Navy Departments in 1940, it was obvious that for emergency operations NAS, working through NRC, was handicapped by certain features inherent in its organization. In the first place, the Academy had been set up to give advice to Government Departments as and when requested. It had no authority to offer unsolicited advice, nor to require more information from a Government Department in preparing its reports than that Department chose to disclose. It had no research facilities of its own and was not expected to conduct research. Its strength and authority lay chiefly in its position as the highest consulting group in American science.

Furthermore, the Academy could not function as a Government executive agency because its status was only quasi-official, the President of the United States had no direct control over it, and it received no funds directly from Congress.

The National Advisory Committee for Aeronautics, organized in 1915, was an important research organization of a radically different character. It had been established by Act of Congress just before our entry into World War I to "supervise and direct the scientific study of the problems of flight with a view to their practical solution" and to "direct and conduct research and experiments in aeronautics." Its funds came directly from Congress. Since its establishment a regular increase of its appropriations had enabled the Committee to construct extensive laboratories and wind tunnels, to build up a competent research staff, and to enter into contracts with educational institutions and private laboratories for carrying out specific research assignments. The administration of NACA was unique among Government scientific agencies in that its controlling body, although a committee appointed by the President of the United States, served without salary. This gave it great independence. Of the fifteen members of NACA, two were from the Army Air Force and two from the Navy, which insured appropriate consideration of all problems of military aviation. The Navy deserves credit for having been one of the original sponsors of this agency and for having given it office space for the first twenty-five years of its existence.

4. NDRC AND OSRD

It was fortunate that, when World War II broke out, NAS and NACA were headed respectively by such forward-looking men as Frank B. Jewett and Vannevar Bush. After Germany's attack on Poland in September 1939, Dr. Jewett brought together as an informal committee a few of the key scientists of the National Academy to discuss the steps that should be taken to utilize to the fullest extent possible the scientific potential of the United States should we be drawn into the conflict. The outcome of these discussions was the action taken by the Council of National Defense on June 27, 1940, creating the National Defense Research Committee. Dr. Bush was named Chairman.

The National Defense Research Committee was directed by its charter to correlate and support scientific research on all mechanisms and devices of warfare except those relating to problems of flight, which were included in NACA's field of activities. In doing this, it was to aid and supplement the experimental and research activities of the War and Navy Departments and to utilize wherever possible existing Government facilities, such as the National Bureau of Standards. It was not expected to take over the work the Army and Navy were doing either in their own research establishments or by arrangement with industry. After its establishment, NDRC carried on its research and development activities by contracts made with individuals, educa-

NATIONAL DEFENSE RESEARCH COMMITTEE, MAY 1945

Back Row: Karl T. Compton, President M.I.T.; Roger Adams, Univ. of Illinois; Conway P. Coe, Commissioner of Patents; Irvin Stewart, Secretary O.S.R.D.

Front Row: Frank B. Jewett, President N.A.S.; Rear Adm. Julius A. Furer, U.S.N., Coordinator Res. and Devlp. Navy; James B. Conant, President Harvard Univ.; Richard C. Tolman, Cal. Inst. of Tech.

NOTE—Captain Lybrand P. Smith, U.S.N., represented the Navy on this Committee from its formation until March, 1945, when he had to retire because of ill health. No picture is available of the NDRC during that period. The Army representative is also absent from the picture. There were many changes in Army representation. The civilian members remained the same throughout the war.

tional institutions, scientific bodies such as NAS and NRC, and industrial organizations. This work was financed with funds appropriated directly by Congress or transferred to it from the appropriations of the War and Navy Departments. NDRC neither established laboratories of its own nor permitted members of its staff to conduct research, but worked through contractors in all of its many fields. As for internal organization, it was divided into Divisions which in turn were subdivided into Sections for administering the work to be performed. Broadly speaking, each Division and Section was built around a specific functional concept, such as the development of fire control, of radar, sub-surface warfare, etc.

After carrying on for a number of months as an agency of the Council of National Defense, it became apparent that NDRC would be able to accomplish its purposes more effectively if it were linked more closely with the Office of Emergency Management and thus placed directly under the President. Accordingly, an Executive Order of June 28, 1941 created the Office of Scientific Research and Development in the Executive Office of the President, and gave to it control over NDRC. Dr. Bush was made Director of OSRD.

Opportunity also was taken to expand the scope of activities and responsibilities of the original organization, to meet certain needs that had become noticeable. No provision had

been made for the stimulation of research in the field of military medicine. To correct this, a Committee on Medical Research, paralleling NDRC in its purpose and method of operation, was created by the Executive Order and included as a component of OSRD. Later other activities, such as the Scientific Personnel Office and the Office of Field Service, were added to round out the organization.

In visualizing the mission of NDRC at the time of its establishment, insufficient stress had been placed on the development of instruments of warfare in contradistinction to the research on which such developments would be based. It became increasingly apparent during 1940-1941 that, if the research sponsored by NDRC were to be made really effective, it would have to be carried through engineering development and field testing. In the end, OSRD even entered the field of production by sponsoring a number of crash programs for limited numbers of urgently-needed weapons and devices, such as rockets and certain kinds of radar equipment. The general policy, however, was for OSRD to act as a procurement agency for the Services only in very unusual circumstances, where there was no practical alternative if new equipment was to be delivered to the front in time to be of the greatest value.

In a number of instances, after beginning research OSRD turned its projects over to the Services for completion of the research work and the carrying out of the development programs. The two most notable examples were those of the atomic bomb, which was turned over to the Corps of Engineers of the Army, and of the proximity fuse, which was turned over to the Bureau of Ordnance of the Navy. OSRD continued to furnish most of the scientific personnel for these projects, robbing NDRC whenever the importance of the weapons being developed made this necessary. The way these programs were handled furnishes interesting examples of the flexibility of the OSRD organization and of the close relationship that existed between the Armed Services and civilian scientists.

Thus the creation of NDRC and OSRD filled the gaps existing in the plan for utilizing American science in World War II. It remains now to mention an even more important matter than the organization and administrative procedures that were set up to this end—namely, the philosophy of the men who devised the organization. The four men chiefly responsible for establishing the new organization were Frank B. Jewett, President of the National Academy of Sciences and of the Bell Telephone Laboratories; Vannevar Bush, President of the Carnegie Institution of Washington; Karl T. Compton, President of the Massachusetts Institute of Technology; and James B. Conant, President of Harvard University. All were of outstanding ability as administrators as well as scientists. All had seen service with the Armed Forces during World War I in positions providing opportunities for first-hand observation of the problems of modern warfare and of the working of the minds of professional military and naval men in dealing with them.

Their estimate of the situation and their plan for meeting it reflected this experience. As summarized by Dr. Irvin Stewart, the Deputy Director of OSRD, the position they took was as follows:

"Previous efforts to bring civilian science into the program of weapon development were based on the theory that the Services would know what they needed and would ask the scientists to aid in its development. Modern science has progressed to the point where the military chieftains were not sufficiently acquainted with its possibilities to know what they might ask with a reasonable expectation that it

could be developed. The times called for a reversal of the situation, namely letting men who knew the latest advances in sciences become more familiar with the needs of the military in order that they might tell the military what was possible in science so that together they might assess what should be done. It was this conception which Bush and his colleagues sold to President Roosevelt and to which General Marshall and Admiral Stark gave their blessing prior to the issuance of the order of the Council of National Defense, which on June 27, 1940, established the National Defense Research Committee of the Council of National Defense".[1]

5. THE NAVY'S NEED FOR A CO-ORDINATING LINK

This concept of the founders of NDRC was eminently sound but, as so often happens, theory and practice did not fall into step automatically and immediately. During the early months of 1941 a situation developed which highlighted the need for a co-ordinating link between civilian science and the Navy. In the fall of 1940, when German submarines were making alarming inroads on British sea power, the Navy Department had requested the National Academy of Sciences to study the scientific aspects of antisubmarine warfare and to ascertain the adequacy of the weapons and procedures being used to combat the U-boats. In response, Dr. Jewett appointed a special committee headed by Dr. E. H. Colpitts to study the subject. The committee's report and recommendations were sent on January 31, 1941 to the Technical Aid of the Secretary of the Navy, who at that time was also the Director of the Naval Research Laboratory. After a month had passed without word of any action having been taken on these recommendations, Dr. Jewett urged that the report be brought to the attention of the Secretary of the Navy, the Honorable Frank Knox. The Director of the Naval Research Laboratory thereupon, on 17 March, 1941, forwarded the report to the Secretary with comments that were in general hostile to the recommendations themselves and to a lesser degree to the method proposed by the committee for carrying them out.

The last two sentences of the forwarding letter were particularly disturbing to Mr. Knox: "It would appear at the present time that the only reason for acceding to such a recommendation would be on account of the pressure exerted by certain well-known scientists, some of whose names appear in this correspondence. It is obvious that such an agency must be subordinate to the Naval Research Laboratory and should be under the charge of a Naval Officer who is entirely sympathetic to research." As a matter of historical record it should be stated that the disagreement of the Director of the Naval Research Laboratory with the Colpitts report was ultimately resolved at a high level in favor of carrying out the committee's recommendations, but this did not alter the fact that there had been a clash at the very beginning on an important principle of collaboration between civilian scientists and the Navy.

Secretary Knox was quick to see that this attitude on the part of the Navy, if allowed to prevail, would seriously impair the effectiveness of such collaboration. Accordingly, in March 1941 he requested Dr. Jerome C. Hunsaker to study the problem and to advise him of the steps that might be taken to correct the situation. Dr. Hunsaker[2] was a particularly happy choice for this assignment. He had the combination of a distinguished early career in the Navy and of later close

[1] Irvin Stewart, *Organizing Scientific Research for War*, Boston, Little, Brown, 1948, p. 6.

[2] He was the Navy's pioneer aeronautical engineer, dating from his graduation from the Naval Academy in 1908, and had been the Navy's outstanding aviation expert until his resignation from the Service in 1926.

Official U.S. Navy Photograph

Advisory Council Office of Scientific Research and Development during World War II. Left to right: Dr. J. C. Hunsaker, National Advisory Committee for Aeronautics; Mr. H. H. Bundy, representing Secretary of War; Dr. J. B. Conant, National Defense Research Committee; Dr. V. Bush, Director O.S.R.D. (Chairman of Council); Rear Admiral J. A. Furer, U.S.N., representing Secretary of the Navy; Dr. A. N. Richards, Medical Research Council; Dr. F. B. Jewett, National Academy of Science; Dr. C. L. Wilson, Deputy Director O.S.R.D.

association with many of the leading scientists in the United States and Europe. At the time of Secretary Knox's request he was Head of the Department of Mechanical and Aeronautical Engineering at the Massachusetts Institute of Technology, the Chairman of NACA, and the Treasurer of the National Academy of Sciences. He had the complete confidence of his former associates in the Naval Service, many of whom had by that time reached positions of high rank and authority in the Navy.

Another matter involving research had also arisen on which the Secretary desired advice. In January 1941 the Director of the Naval Research Laboratory had recommended to the Secretary that the Navy's policy as regards research and the status of the Naval Research Laboratory be reexamined. Among other things he recommended that the Laboratory be given Bureau status, that its name be changed to "Navy Research Center," and that it be authorized to supervise all research for the Navy wherever conducted. This letter was referred by the Secretary of the Navy to the General Board for study and recommendation.

The General Board held hearings on the subject, and in its report of 22 March 1941 stated that it did not concur in the recommendations submitted. It proposed the establishment instead of a Naval Research Council to advise the Secretary on Naval research policy in general and on the co-ordination of research within the Naval Establishment in particular. The Secretary referred the report of the General Board to Dr. Hunsaker for consideration in connection with the study he was already making. Secretary Knox desired advice also on a third subject.

Great numbers of suggestions for improving naval weapons, devices, and practices are received by the Navy Department from the public at large in peace as well as in war. They range all the way from impractical notions to creative thinking of a high order. Some are accompanied by finished engineering plans. Some are of questionable honesty. Every year such hardy perennials as the mysterious and secret chemical for converting water into gasoline appear. Many of the ideas submitted over the years have, however, had substantial merit. The Navy department therefore encourages the public to submit its suggestions.

A desk in the Executive Office of the Secretary for handling such matters goes back to World War I, when the job occupied the full time of Rear Admiral William Strother Smith, who was Technical Aide to the Secretary. The desk proved particularly valuable in screening out things that were obviously impractical, thereby saving the time of busy people in the technical Bureaus. It channeled the ideas that had merit to the Bureau that had cognizance of the subject. The fact that any one interested in such matters could without delay obtain a personal interview with a senior officer close to the Secretary of the Navy, had a good psychological effect. During the interwar period the desk had grown until it had half a dozen employees.

In order to meet the Secretary's request for advice, Dr. Hunsaker's task was therefore one of making recommendations on three subjects — how best to promote the effective collaboration of organized civilian science with the Navy, what mechanism to adopt for co-ordinating the research and development activities of the Bureaus and other technical divisions of the Navy Department itself, and what steps to take to improve the handling of the suggestions on weapons, devices, and practices flowing into the Navy Department from the public at large. The last mentioned offered no problem. The National Inventor's Council had shortly before been set up to foster and to stimulate creative thinking by the public on military inventions.

Closer liaison between the NIC and the Navy Department's office handling such matters was indicated and put into effect when that office was made a unit of the about-to-be-created coordinator's office.

Dr. Hunsaker considered the first mentioned as the most important of the subjects he was studying for the Secretary. At the outset he adopted the principle that any mechanism set up in the Navy Department for promoting collaboration with civilian research organizations must function along co-operative rather than authoritarian lines. The procedures set up must stress advising, guiding, helping, and persuading rather than directing and ordering. He suggested the title of Coordinator of Research and Development as descriptive of the over-all mission of the new office to be established for this purpose.

The principal points included in Dr. Hunsaker's philosophy were that the Coordinator should report directly to the Secretary of the Navy and that his office should not form part of the organization of the Chief of Naval Operations; that the Naval Research Laboratory should be returned to the Bureau of Ships so as to free the Coordinator from the direct administration of research and development programs that might be in competition with NDRC; that the number one mission of the Coordinator's office would be to facilitate and to assist the work of civilian scientists in their dealings with the Navy; that effective liaison and close personal relations between the civilian scientists and the Bureaus, OCNO, and the Fleet would be essential and would have to be promoted by the Coordinator in order to sell many of the new ideas that would be advanced by the scientists; and that a secondary mission of the office would be the co-ordination of the research activities of the Bureaus through a Board presided over by the Coordinator and consisting of representatives of the Chief of Naval Operations and of the respective Bureaus.

The decision to keep the Coordinator's Office free from the administration of actual research was sound.[1] It was considered likely, and this was confirmed by actual experience, that civilian scientists would turn to the Coordinator's office with new ideas much more freely if it were not in competition with them in actual research. So much of the Coordinator's work turned out to be the umpiring and refereeing of other people's disagreements that a disinterested position was essential. His office became increasingly effective in this respect as the Bureaus and other offices of the Navy Department, the War Department, and the civilian scientists gained confidence in it.

The temptation was great on many occasions to undertake the active direction of research on the grounds of urgency. This was especially true of projects that were crying for solution but which did not come under the cognizance of any one Bureau or division of the Navy Department. In such cases the Coordinator initiated the projects and then turned them over to the sponsorship of an appropriate activity. One of the problems was to keep his own staff satisfied with the workaday role of opening doors for others. As most of the staff were scientists themselves, this was a hard decision for many of them to accept. However, they made the sacrifice and stuck to what was generally the thankless job of ironing out the infinite variety of complicated human relations involved in the introduction of new ideas, and in assisting others to work effectively.

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[1] In 1945 the writer, as Coordinator of Research and Development, sponsored a *peacetime* organization for handling Navy Research which has developed into the present Office of Naval Research. Included in its functions is the administration of certain research, but this is not inconsistent with the above because in peacetime there is no emergency civilian organizations such as OSRD whose work needs to be coordinated with that of the military services.

6. ESTABLISHMENT OF THE OFFICE OF THE COORDINATOR

After approval by the secretary of the Navy of the basic principles recommended by Dr. Hunsaker, General Order No. 150 was drawn up to implement broadly the decisions that had been reached. The order was issued as of July 12, 1941, under the title "Coordination of Research and Development." This was about a year after the creation of NDRC, a few weeks after the establishment of OSRD and approximately five months before Pearl Harbor.

Dr. Hunsaker did not succeed in obtaining for the Coordinator's office all of the authority it needed to insure the maximum in effectiveness, but what he got was enough to enable civilian organizations such as OSRD to work effectively with the Navy. As the result of experience, some functions were added, a few modifications were made, and increasing emphasis was placed on liaison, but no departures from Dr. Hunsaker's basic principles were found necessary during the war. The detailed procedures for accomplishing the main objectives were worked out as problems were encountered; in many respects the resultant formulation of effective operating principles was even more important to the success of the Coordinator's mission than was the original statement of the principles to be followed.

The General Order stipulated that the Coordinator of Research and Development must be a civilian scientist, and Dr. Hunsaker was at once appointed to that position. However, in view of his duties as Chairman of NACA, he requested that his assignment be considered temporary and that he be relieved as soon as the office was functioning well and a suitable individual could be found to fill his place. The idea on which the appointment of a civilian scientist was based was that such action would give the civilian scientific organizations confidence in the office and thereby would facilitate their dealings with the Navy. It was soon found that it was even more necessary to persuade the Navy to have confidence in the civilian scientific organizations and to gain some appreciation of their capabilities. Accordingly, after the key personnel of the new office had been selected and the office itself had been in operation a number of months, the Secretary of the Navy, on Dr. Hunsaker's advice, decided that a Naval officer should be appointed as Coordinator. Before this could be done, however, General Order No. 150 had to be amended to make the action possible. This was done by General Order No. 159, of December 1, 1941, and Rear Admiral Julius A. Furer, U.S.N., an officer of the former Construction Corps of the Navy, was selected for the position. He relieved Dr. Hunsaker as Coordinator of Research and Development on December 13, 1941, and served as such throughout the war, until the functions of the office were absorbed by the newly-established Office of Research and Inventions.

7. THE MISSION OF THE COORDINATOR

Diverting the scientific manpower of the United States from normal into war-making channels fortunately did not involve the Government in all of the perplexing problems that had to be confronted in converting industry from peace to war production. Problems such as the prevention of profiteering, meeting the demands of organized labor, and fitting civilian needs into military programs were nonexistent, but others no less difficult to handle had to be solved. From the point of view of Dr. Bush and his colleagues, two outstanding requirements had to be met before the scientific potential of the country could be utilized to the utmost in the war. These were that scientists be given full opportunity to become acquainted at first hand with modern warfare, even to the extent of having a voice in strategic and tactical

COORDINATOR OF RESEARCH U.S. NAVY AND OFFICER STAFF, FEBRUARY, 1945

Back Row: Lt. A. C. Body; Lt. Cdr. N. S. Bartow; Lt. J. H. Wakelin; Lt. (jg) B. A. Cowie; Lt. Cdr. J. P. Parker; Lt. Cdr. B. S. Old; Lt. Cdr. J. T. Burwell.

Front Row: Lt. Cdr. R. A. Krause; Captain L. P. Smith, U.S.N.; Rear Admiral J. A. Furer, U.S.N.; Captain S. F. Smith, C. C. U.S.N.; Cdr. R. D. Conrad, U.S.N.; Lt. Cdr. H. G. Dyke.

planning, and that the Armed Services clear away obstructions and red tape so as to make it possible for them to work in their accustomed ways.

The first requirement meant that the civilian scientists would have to be taken into full partnership with the Services instead of being kept in the position of hired men who do only what they are told to do. The higher echelons in the Navy, especially those in the line, asked whether this was necessary, whether it was safe from the point of view of security, whether it was practicable. Even in the regular Navy the engineer and the scientist did not sit at the head table with the line officer in all matters of war planning. For this reason, the principle of full partnership could not have been stated in so many words in any order issued in the spring of 1941, and in fact was never so stated officially; in any case, it could not have been accomplished by fiat. Dr. Hunsaker and his successor realized this but nevertheless considered that bringing about such a partnership in principle was in the broadest sense the Coordinator's mission. This required the Coordinator to persuade the Navy, at some levels and in some branches, that the civilian scientists were competent, reliable, well organized, and ready to undertake any problem lending itself to the scientific method for solution, and that they were eager to assist the Navy in all undertakings of that kind.

In most quarters the scientists were accepted without question, but, for the reasons already mentioned, some activities hesitated to open their doors. This was especially so in places where the Navy was already carrying on its own secret research, in virgin territory such as operations research, and in field-service activities where oversea transportation and accommodations for civilian scientists presented difficulties. With the growth of confidence in the Coordinator's Office and in the scientists themselves, resistance gradually diminished.

As to the second requirement, few know better than those who have spent a lifetime in the Government's service the difficulties of doing business with the Government. There are always the problems of finding who handles what, whom to see first, how far an individual's authority and responsibility go, when to talk and when to write, and the hundred and one other minutiae of procedure that constitute what is commonly known as red tape. As these problems are often baffling to even the most experienced Government employees, it was realized that they would be appalling to most of the scientists, few of whom had had any experience in dealing with the Government. No special pleading on the part of the scientists was therefore necessary to convince the Coordinator that an important part of the mission of his office would be to assist them through the mazes of officialdom. Bringing the right people together at the right time, opening doors, eliminating unnecessary steps, educating the scientists as to the irreducibles of orderly procedure, were all services that proved to be of tremendous help in speeding up scientific research.

Thus it was that liaison work for the scientists became the Coordinator's primary mission. At the highest level the liaison between the Navy and OSRD consisted of the Coordinator, as the Navy member of the Director's Advisory Council, and of the Coordinator's senior assistant as the Navy member of NDRC. Dr. Bush's Advisory Council was a small group which remained unchanged throughout the war and consisted, in addition to the Navy member, of the chairmen of NDRC, CMR, and NACA, and of a War Department representative.

During the first eighteen months of OSRD's operations many important problems of relations with the Armed Services required handling by the Ad-

visory Council. These included pressing for action on programs that were lagging and in stimulating Service interest in the ideas advanced by the scientists. By the end of 1942 the principal lines of activity were well in hand and the need for frequent meetings of the Advisory Council had passed. A further reason was that, when in May 1942 the Joint Committee on New Weapons and Equipment of the Joint Chiefs of Staff was established, with Dr. Bush as its Chairman, the scientists were able to obtain a hearing for their ideas at the highest level without passing through liaison channels. This, of course, left unchanged the great need for effective liaison at lower levels.

When in the fall of 1944 the Director of the OSRD saw the end of the war in Europe approaching and began making plans for the orderly demobolization of his organization, there was strong resistance from some branches of the Army and the Navy on the grounds that they were being left in the lurch by the civilian scientists before the war was over. The Navy Coordinator agreed with Dr. Bush that the preparation of such plans was timely and should proceed. In supporting before the Naval Research and Development Board the steps that Dr. Bush proposed to take, Rear Admiral Furer found himself in a position which, curiously enough, appeared to be the reverse of the one he had held from the beginning. The situation was resolved satisfactorily to the Navy when Dr. Bush, through the Coordinator, made it clear that the OSRD would continue to accept projects that had any chance of becoming effective in the war in the Pacific, and would either complete all projects under way or turn them over to a Service activity.

Navy membership on the National Defense Research Committee, on the other hand, was much more than a matter of providing liaison at this level between the Navy and this particular organization. The Navy member actually had the same authority and responsibility for the overall administration of NDRC activities as had the other seven members of the Committee.

Clearance to spend money on an urgently-needed NDRC project was often given informally, usually on the recommendation of a Division chief, before the Committee was in possession of all of the information needed to take definite action on the project. It was the special business of the Navy member to inform himself fully and to present the case to the Committee for all projects in which the Navy had or might have an interest, whether or not the request had originated with the Navy. This was a full time job in which the Coordinator's senior assistant Captain Lybrand Smith, U. S. N. was ably assisted by the various members of the Coordinator's staff. The arrangement had the advantage that it brought all the officers of the staff in on the ground floor of all projects.

At the very beginning the Coordinator adopted the policy that the Navy member need not necessarily be bound by any lack of interest, expressed or otherwise, on the part of the Navy in any research and development work under discussion by NDRC. For example, the Navy technical services concerned took a very dim view of the future of rockets when intensive research in this field was first considered by NDRC. The Navy member nevertheless advocated immediate and all-out research and development in this field. Subsequent events proved the judgment of the Coordinator's office to be correct, for rockets became one of the most valuable weapons of amphibious warfare in the Pacific.

The furnishing of competent liaison by the Navy for individual research and development undertakings was recognized as of the utmost importance; only by such means could the

needs of the Navy be defined and some guarantee obtained that the product of the development would meet them. One of the responsibilities of the Coordinator's Office was to arrange for such liaison. The rapid development of a reliable new weapon or device is largely a matter of good team work by the scientist, the engineer, the manufacturer, the inspector, and the field engineer who introduces it to the Service. Good team work can in turn be insured only by providing competent liaison among the members of such a team. The primary purpose of scientific liaison is to bridge the gaps in the knowledge and experience of the various individuals participating in and responsible for the development.

Scientists mobilized from educational institutions were particularly lacking in knowledge and experience of the practical side of making war. While the Coordinator endeavored to provide opportunities for them to become informed at first hand of the service requirements for every project undertaken by them, it was obvious that all of the research and development workers on a given project could not be given a complete education of this type. Even if that had been possible, intelligent and well-informed liaison would still have been necessary to insure proper attention to the many considerations involved in proceeding from an idea to a satisfactory finished product suitable for use by the Navy. The bare mention of a few requirements of this type will suffice to illustrate what is meant. Materials used by the Navy must be resistant to tropical sea atmospheres and to salt water exposure; limitations on weight and space for shipboard installations can never be ignored; resistance to gunfire shock is a primary consideration; spare parts are essential; the problems of maintenance and operation under the most adverse conditions must be considered from the inception of a project. Innumerable other minutiae must also be considered in producing equipment for the Navy.

To meet the demands of such liaison, the policy was followed of associating with each research undertaking one or more officers whose primary function was to keep the Navy's requirements, particularly the user's point of view, constantly before the scientists during research, development, and evaluation. These officers were nominated to the Coordinators office for record and briefing, and their names were then transmitted to OSRD or other organization concerned. They were selected after consultation with the Coordinator's office by the cognizant Bureau, or in some cases by the operating forces, for their practical knowledge of the conditions to be met. Frequently they were the officers who had taken part in the earliest informal discussions leading up to the project. Their interests and responsilibities frequently extended beyond the laboratory into the engineering stage, and often into crash programs. Some of the liaison officers went to sea with new equipment for extended periods, performing in this way the functions of field engineers. Where the research activity was of sufficient magnitude, as, for example, at the Radiation Laboratory at the Massachusetts Institute of Technology and the ordnance program at the California Institute of Technology, full-time liaison officers with staffs were detailed in addition to the officers appointed for specific projects.

The effectiveness of liaison depends largely on the competence of the liaison officer himself, especially on his ability to adapt himself to the complexities of human nature. Satisfactory liaison was considered so important by the Coordinator that he made it a point to let the scientists know that complaints on this score (or any other, for that matter) could be safely lodged with the Coordinator without jeopardizing the scientist's standing and good relations with the Navy. It was laid down

as a principle that the function of the liaison officer was to advise the scientist as to service requirements and needs, to point out wherein and why a device fell short of meeting such requirements, and to provide any assistance requested, but that it was no part of his job to give directions for accomplishing the results desired. A few liaison officers attempted to instruct the laboratories in how to carry on research. This always caused trouble, because no scientist can work creatively with someone looking over his shoulder telling him what to do. A number of changes in personnel had to be made to correct such situations.

II. THE OPERATION OF THE ORGANIZATION

1. THE WARTIME OFFICE OF THE COORDINATOR.

The establishment of the Office of the Coordinator of Research and Development in July and the appointment of a Naval officer as Coordinator in November 1941 brought to an end the period of planning for the co-ordination of Naval research and development. The general principles to be followed by the new Office in establishing and maintaining effective liaison with the civilian scientific organizations had been stated, a program for coordinating research and development activities within the Navy itself had been formulated, and the new organization had been given definite status in the Navy Department. What remained to be done was the translation of general responsibilities and principles of action into efficient, smoothly-functioning measures of wartime operations. This section will describe the means and methods by which these objectives were accomplished.

a. The Selection of Staff Members

In planning the new organization, Dr. Hunsaker had realized that its usefulness would depend largely on the competency and adaptability of its staff. Because there were neither precedents nor past experience to use as a guide, the staff members first selected would be pioneers in a new field of liaison procedures. Each officer would have to deal with a wide variety of complex technical matters; he would have to come to know personally a great many civilian scientists and officers in the Army and the Navy, whose complete confidence he must gain; he would have to acquire an understanding of the relations among numerous activities and the conflicting interests that often would arise between them. For these reasons, it was believed that Naval Reserve officers with backgrounds of scientific education and research experience would most likely be able to work sympathetically with civilian scientific organizations.

In the summer of 1941 the Navy did not have a roster of scientific personnel from which a list of such men could be compiled (such a roster was later established for the country as a whole, under the auspices of OSRD). The Bureau of Navigation, had however, classified the Reserve officers of the Navy according to their civilian professions. The cards of several hundred Reserve officers in the scientific and engineering categories were examined, and from these, twenty-five likely candidates were selected for personal interviews. From this number, four whose records and personalities indicated outstanding qualifications for liaison work were chosen. They and two officers from the regular

Navy made up the staff when the author relieved Dr. Hunsaker as Coordinator in December 1941. The staff was subsequently increased by the gradual addition of other Reserve officers. A Reserve officer with experience in patent law was also added to the Office of Inventions. A civilian force with a small nucleus of employees of long service in the Government had also to be built up to meet the ever increasing activities of the office.

There were no supernumeraries among the officers or the civilian employees of the Office of the Coordinator. The force was very small, as measured by the concepts of adequacy that prevailed during the war, but it was large enough to carry out the mission of the Office as long as it was limited to the function of co-ordinating research. What the force lacked in numbers it made up in competency of an exceptionally high order.

b. General Procedures

"Red tape" has been the curse of government since the beginning of organized society. There is good reason for red tape, however, because orderly procedure—another name for red tape intelligently applied—is needed to control correspondence and to fix authority and responsibility. At the beginning of the war, most of the scientists mobilized by OSRD resented working in channels, for few of them had ever worked as members of large organizations. Before the war ended most of them had come to acknowledge the need for orderly procedure and channelized correspondence.

One of the objectives of the Coordinator's Office was to speed up orderly procedures. To this end the policy was adopted of starting all new projects with informal discussions (not correspondence) and bringing in on the ground floor so far as possible all those with ultimate cognizance over the matter. Such discussions were followed immediately with a written statement of the decisions reached. The next step was a carefully planned conference at which the Coordinator usually presided. The right people at appropriate levels were invited to attend, and a clear cut agenda of the ground to be covered was prepared. The principal job of the chairman was to keep the conference on the subject without restricting discussion, to arrive at a clear understanding of the agreements reached, to determine on the next steps to be taken and the individuals to take them. The minutes of conferences were prepared immediately and distributed to those who attended so as to avoid lapses of memory and waning enthusiasms. The Coordinator's staff handled all of the details of conferences, such as the preparation of agendas and minutes and the follow-up on next steps to be taken. The conference technique was developed to a high degree of effectiveness in getting research projects under way quickly and in keeping them moving.

As a result of the emphasis placed by the Coordinator on informal methods as a means of getting things started, by the summer of 1942 the Bureaus began to take up new work directly with OSRD. Had this practice been continued, it would have led to much confusion and many difficult situations. Accordingly, all Bureaus and offices of the Navy Department were reminded by the Secretary of the Navy that all requests for research made of non-Naval agencies must be channeled through the Office of the Coordinator, as required by General Order No. 150. This was one of the few formal directives issued by the Coordinator.

c. The Intelligence Analysis Section

An Intelligence Analysis Section (not included in the original organization of the Coordinator's Office) was soon found to be essential. No provision for performing this function had originally been made because it had been assumed that the Office of Naval Intelligence would be able to appraise incoming

information for its scientific research value and would forward reports on such information to either the Coordinator's Office or the interested divisions of the Navy Department. The magnitude of this task, had however, been very much underestimated. When we entered the war, information began to flow into the Office of Naval Intelligence, the Military Intelligence Division of the War Department, and the Office of Strategic Services in greatly increased volume and from many new sources. To the reports from Military, Naval, and Air Attachés were added reports from secret agents, prisoner of war interrogations, captured enemy documents, battle action reports, ship-sinking survivor reports, industrial bomb-damage reports, briefs of State Department telegrams and dispatches, and excerpts from scientific and technical journals. Most of these reports did not deal primarily with scientific and technical matters but often contained clues as to weapon development under way in enemy countries. For the most part, however, information of this kind was so obscured by unrelated matter that it could not readily be recognized as having research value. It soon became evident that the personnel in ONI qualified to screen out information of this kind was insufficient for the task, and so an Intelligence Analysis Section was set up as part of the Coordinator's organization.

In selecting an individual to head this section, the Coordinator was governed by the belief that a scientist was not needed. Scientists were scarce and a good one would not in any case have been interested because of the drudgery involved, especially as the mission of the Section was not to include evaluation of the information uncovered. The most important qualities in a candidate for the assignment were considered to be a large store of general knowledge (rather than specific scientific information), an active and vivid imagination, a good memory for details, patience and perserverance beyond the ordinary, and experience in searching written reports for obscure information. On this basis a young lawyer from the Department of Justice was selected who had specialized in searching corporation reports and files for evidence to be used in preparing antitrust suits. His services proved highly satisfactory.

This Section became also the working unit of the Coordinator's Office in its dealings with the liaison office of OSRD, which was established to handle the flow of scientific and technical information among the Lend-Lease countries. The object of this interchange was not merely to provide files in Washington and in London containing information on the latest wartime developments in the two countries, but it was also to get this information as quickly as possible into the hands of all those who needed it in their work on new weapons. The Coordinator's Office received duplicate copies from the OSRD liaison office of all reports that were clearly of interest to the Navy, and also complete lists of all the reports the OSRD office obtained. The Intelligence Analysis Section scanned the reports sent it (more complete studies of the principal reports were made by the staff specialists) and checked the OSRD daily accessions list to determine whether the distribution indicated for each item fully covered the Navy's needs. The process of scanning reports included taking up personally with the staff specialists concerned any additional distribution that might be useful. The staff specialists in the Coordinator's Office frequently checked with individuals and offices they knew to have an interest in a subject to make sure the reported information had been received. As a result of such procedures, frequently the first word that new information was available on a

subject came from the Coordinator's Office.

When that Office became adept in determining accurately and quickly where intelligence and scientific reports should go, an arrangement was made with ONI and OSS for it to receive an additional copy of certain kinds of reports; of special importance in this respect were reports dealing with the performance of new weapons under combat conditions and containing scientific and technical information about enemy weapons. The Coordinator's Office assumed responsibility for routing such reports to the civilian scientific organizations in need of the information. The normal channel for reaching the subdivisions of NDRC was through the OSRD liaison office, but routine forwarding was supplemented in all important matters by personal contacts. This policy was also pursued in apprizing certain offices in the Navy Department of important developments.

Information having special significance was promptly and informally brought to the attention of responsible individuals in the organizations of CNO, CominCH, the Bureaus, and other offices in the War and Navy Departments, as well as the interested civilian research groups. Dossiers were set up on important subjects, especially on those having to do with the enemies' new weapon developments. As an example of the results thus obtained, the Coordinator's Office was the first to deduce from intelligence reports that German guided missiles such as the HS293, the V-bombs, and acoustically-steered torpedoes would soon appear. The dossiers on these and other subjects were frequently consulted by various offices of the Navy Department, the War Department, and the NDRC groups. As a result, studies of countermeasures were begun before the enemy weapons actually made their appearance in combat. Incidentally, the Coordinator's files were the most complete in Washington on these subjects.

The steps taken to piece together random bits of information into something of constructive value did not follow a uniform pattern. Each case called for individual treatment. The expected appearance of a German acoustic torpedo provides a good illustration of how an important case of this kind was handled.

The Coordinator's Office felt from the beginning that sooner or later a German torpedo of the homing type would appear. Such a weapon could be built around any one of several physical principles, but until it was known what principle had been adopted it would be difficult to plan effective countermeasures. Such a torpedo could be made to home on sound coming from the target (ship propeller noises, for example), on echoes reflected from the target, on electromagnetic disturbances, or on a combination of any of these. The Intelligence Analysis Section was early on the lookout for any information indicating that the Germans had such a weapon under development. In February 1943 a German submarine survivor dropped a remark that a new type of torpedo was under test in the Baltic. This little item, appearing as it did in a routine prisoner interrogation report, caused a stir in the Coordinator's Office because it confirmed a long-held surmise.

A study of ship-sinking reports from all parts of the world was immediately begun. If the Germans had a new torpedo in process of development, it was felt that they would certainly try it out on merchant ships in remote areas before they would place it in full-scale production for service use. The analysis personnel looked particularly for any report of the erratic behavior of torpedoes just before striking their target. A study of 368 ship sinking reports revealed seven widely scattered observations of torpedo behavior that was erratic beyond the conventional

broaching, circling, and porpoising. A report by two survivors of the Amerifreighter *Robert E. Lee,* sunk by a torpedo off the mouth of the Mississippi, was considered particularly significant. The survivors stated that shortly before the explosion they had seen what appeared to be a shark swimming parallel to the ship's course some distance away, and that suddenly the shark had turned at right angles and made directly for the ship; the explosion occurred a few seconds later.

The suspicion that a German homing torpedo was about to be introduced was communicated to the appropriate office in the Navy Department, and ONI was alerted to have submarine-survivor prisoners interrogated as to their knowledge of such a torpedo. One officer from ONI was assigned to work full time with the Coordinator's Office in running down all leads. He had been a teacher of German and history before enrolling in the Naval Reserve and had a wide acquaintance with German technical terms, although he was not an engineer. When he was placed on this assignment he began an intensive study of torpedo development and construction. Before he finished his assignment, he was probably the best informed officer in the Navy on German torpedoes.

In June 1943 a German technical rating was picked up as a survivor from a submarine that had been sunk; he seemed to know a good deal about a new torpedo that was under development, but did not claim to be a torpedo specialist. He gave the Coordinator's representative many details of the construction and operation of the new torpedo, but he either did not know or would not divulge the stimulus to which the control was responsive. It was clear from his descriptions, however, that the control mechanism was based on acoustic and not on echo principles. The staff scientist on acoustics in the Coordinator's Office then began to work with the Underwater Sound Laboratory to develop countermeasures to this type of torpedo. The full range of possible frequencies was explored and various types of clatter boxes and other sound-producing devices were developed which, when towed astern of a ship, would decoy the torpedo away from its target and cause it to exhaust or destroy itself in attacking the decoy. Thus satisfactory countermeasures were actually available when such torpedoes appeared in quantity late in the war.

The facts about the steps taken to meet this menace were quite different from those given in an article in one of the popular magazines shortly after V-J Day, which said that "American experts came up with fourteen answers to the acoustical torpedo in a brief number of hours." The time was more nearly fourteen months from the first intimation that the Germans were working on an acoustical torpedo. Fortunately for us, the lag between the laboratory model and quantity production of the German torpedo was so great that it did not become a surprise weapon.

It is obvious that the work of the Intelligence Analysis Section often duplicated work that was being done elsewhere. Much of the information the Section handled would no doubt eventually have reached its logical destination without the intervention of the Coordinator's Office. Nevertheless, the principle was followed that all information having a bearing on the development and performance of new weapons and devices, whether the enemy's or our own, was highly important, and had to be passed on as quickly as possible to those interested in the subject. It was considered better to incur any amount of duplication in disseminating information than to run the risk of leaving research and development workers in the dark about what was being done elsewhere in the same field. It can safely be said that no duplication paid greater dividends

than this one. The cost was not great and the service rendered was often of immense value.

The success of the Intelligence Analysis Section resulted in setting up a technical information center in ONI toward the end of the war. Until this time ONI had taken the position that it could not appraise technical reports because it lacked the necessary technical personnel, and that its function was simply that of a post office for distributing reports to the Bureaus and elsewhere, for evaluation there. The Coordinator's answer, based on actual experience, was that scientists and engineers were not necessary for the first sifting process, and that the personnel needed by ONI were individuals trained in looking for specific items in masses of data and in voluminous reports. Such items could readily be recognized by alert and interested researchers.

The Coordinator's Office also performed a particularly useful service in organizing the Navy's components of the technical intelligence missions that were set up toward the end of the war to follow the Armed Forces of the United Nations into Italy, France, and Germany. The purpose of these missions was to gather specific scientific and technical information in these countries by interrogating their scientists and laboratories before contact with them was lost. The Intelligence Analysis Section did practically all the initial work of preparing programs for these missions and also much of the briefing of personnel that were sent on them. A member of the Coordinator's staff accompanied the original ALSOS mission to Italy. The Coordinator initiated the arrangements for the formation of a separate Naval Technical Mission to France and Germany, of which the head of the Intelligence Analysis Section became a member. The reports sent back by the missions were handled by ONI.

d. British Relationships and the Interchange of Scientific Information

The pattern for the interchange of scientific information between Great Britain and the United States was determined largely by the way in which civilian scientists were organized for war research in the two countries. In Great Britain nothing comparable to OSRD or NDRC was established. The British mobilization consisted essentially of expanding already existing Government organizations. Ever since the establishment in 1915 of the Department of Scientific and Industrial Research as a separate Department of State, these had covered a much broader field of activities than was represented by Government-sponsored research in the United States. In addition, the British Armed Services had their own research and development establishments, similar to those in the United States. As to personnel, the whole of British scientific manpower was registered in 1939 and thereafter scientists could not enter the Armed Forces without special permission. From this register the research establishments serving the Navy, Army, Air Force, and civilian defense organizations drew their recruits. In neither country were the scientists mobilized as a corps, although many scientists in the United States joined the Armed Services as officers. The fact that as a profession the scientists in both countries retained their civilian status did much to further the program for the full interchange of scientific information.

It had never been the peacetime policy of the British Government to give out information freely about scientific and technical advances that might conceivably jeopardize the commercial or military interests of Great Britain. In the case of the Armed Services, any information given to foreign governments was on an ex-

change basis and was transmitted through accredited representatives of the foreign governments concerned. During World War I the British Admiralty and the United States Navy Department had made technical information available to each other without restrictions of any kind, but immediately after the Armistice the Admiralty closed the doors on this practice. The policy of giving out information only in exchange for information considered to be of equal value was then resumed. This policy had during the peace period preceding World War II almost completely stopped the interchange between the Admiralty and the Navy Department of confidential information on scientific and engineering advances made in the two navies.

British industry was not always happy over this policy and found various ways of circumventing the Admiralty's regulations. The author had an amusing experience of this kind when he was the Assistant Naval Attaché in London from 1935 to 1938. Mr. Scott-Payne, an enthusiastic promoter and builder of high-speed small boats, had persuaded the Admiralty to get out a number of new designs for ship's boats and to adopt gasoline engines for driving the boats. He was also engaged in building for the Admiralty some high-speed motor torpedo boats of his own design. The author wished to inspect and to make a run on one of the M.T.B.'s. Mr. Scott-Payne was equally anxious to have the American Naval Attaché make a report on the boat as he hoped to sell the design to the United States Government or to an American boat builder. The Admiralty however refused permission for an inspection or for a trip on an M.T.B., but gave permission for a visit to Scott-Payne's plant near Southampton to inspect the new types of ship's boats under construction.

The plant manager met the author on the morning set for the visit explaining that Mr. Scott-Payne had found it necessary to personally take one of the M.T.B.'s on a trial run to the Isle of Wight, but that he would be back in time for lunch. In the meanwhile, the inspection of the part of the plant devoted to the building of ship's boats was to be made including a run in one of these boats. Toward the middle of the morning the author and the plant manager shoved off in a ship's boat and headed for the Solent. When the boat was in the vicinity of Calshot the engine suddenly stopped and all efforts on the part of the manager to get it started again were unavailing. On scanning the horizon he exclaimed pointing in the direction of the Isle of Wight, "I believe that is Mr. Scott-Payne coming back in the M.T.B. I must try to attract his attention," which he succeeded in doing. Mr. Scott-Payne came alongside and expressed much concern over the danger to a small boat broken down in the path of large steamers and insisted that the author come on board the M.T.B. for the return trip to the plant. During the run he put the boat through its paces, described its lines and construction, and provided an opportunity for inspecting its accommodations. At lunch he went at length into the tactical uses and advantages of M.T.B.'s. The author, of course, promptly reported the rescue at sea to the Director of Naval Intelligence of the Admiralty and made a full report on the boat and of the episode to the Navy Department. Incidentally, Scott-Payne did eventually sell a motor torpedo boat with its plans to the United States. This was the prototype of the M.T.B.'s which performed so brilliantly in the Philippines and in the Pacific during the war.

When war broke out in Europe, many men in both countries immediately advocated complete interchange between Great Britain and the United States of scientific and technical information about new weapons and

devices of warfare. During the early part of 1940 Lord Lothian, the British Ambassador to Washington, began to press his government for a revision of the traditional barter policy. The authorities in London were, however, loath to change this policy for they believed that Great Britain had more to give than would be received in return. Doubt was also expressed as to American ability to keep secrets. Such considerations shrank into the background with the fall of France and the beginning of air raids on the United Kingdom. These events hastened the realization that Great Britain needed help from the United States in every way, and that chances would have to be taken in the matter of exchange of information.

The first step toward scientific collaboration was the arrival in Washington at the end of August 1940 of a technical mission made up of representatives of the British Ministries, headed by Sir Henry Tizard. This mission was empowered to disclose information about the secret weapons and military devices on which the British were working. The British had already concluded exchange arrangements with Canada in this field and had sent Professor R. H. Fowler to the National Defense Council of Canada to serve as liaison officer between London and Ottawa. In this country the Tizard Mission first made contact with NDRC. Shortly thereafter, the War and Navy Departments authorized NDRC to disclose full information on all research and development projects they had under way.

Both the British and the Americans discovered that the other side was much further advanced in many secret developments than had been expected, and that, in specific lines of research, the gaps in the knowledge of one side were usually also gaps in the knowledge of the other. The British, however, had had twelve months of invaluable war experience, and the fruits of this they now made available to the United States. Among other things, the Tizard Mission gave the United States priceless information about the resonant cavity magnetron, which became the basis of the astounding development of microwave radar on this side of the Atlantic. The conversations of the Tizard Mission with the Armed Services and NDRC touched nearly every scientific aspect of the War.

In a meeting between the Mission and NDRC on September 29, 1940, an arrangement was worked out for the regular and continuous interchange of information about scientific research and weapon development between Great Britain, Canada, and the United States. This was designed to supplement but not to supplant the exchange of information through military and naval channels. A detailed agreement on both policy and procedures was approved by the Secretary of War and the Secretary of the Navy on October 25, 1940; this included a plan for the establishment of an NDRC office in London and of a British scientific office in Washington. It was then up to the British Government to make the next move. High quarters in London again expressed doubt of the wisdom of an unrestricted interchange of technical information, with the result that an invitation from the British Government to put the plan into effect was not received in Washington until January 20, 1941. Dr. Conant was then promptly selected to establish the NDRC branch in London. When President Roosevelt signed the Lend-Lease Act on March 11, 1941, all hesitation about the interchange of scientific information vanished and the British Central Scientific office was established in Washington in April 1941. A steady flow of scientists and technical information between the two countries began, and continued throughout the rest of the war.

The pooling of research reports and

the exchange of visits speeded developments on both sides of the Atlantic. Cross-fertilization of ideas was one of the most valuable products of this liaison. British war experience was invaluable in directing the American scientific effort into the most productive channels. The British no doubt contributed more than they received in the early days of this interchange, but American science and technology from the beginning outranged the British in engineering skill and in the techniques of large-scale production. Also, the effects of the larger reserve scientific manpower of the United States were soon felt.

One aspect of this policy of freely interchanging scientific information deserves special mention. This was how to keep the interchange from jeopardizing in both countries the commercial rights and interests of private contractors engaged in the development and production of war materials. American manufacturers especially felt that technologically they were ahead of British manufacturers, and that in making their technical methods and experience in mass-production available to the British they were impairing their future competitive position in foreign markets. The agreement reached provided that the NDRC would exchange war research information directly with the British Ministries and that information obtained by either Government from its commercial contractors would be made available to the other for Government use only. In practice an informal policy was developed that no information from a commercial contractor of one Government would be divulged by the other Government to one of its contractors without first obtaining the permission of the originating source. This policy was formalized and spelled out in detail in the Radar Exchange Plan, and thereafter was applied in other fields. As a corollary, it was agreed that individuals who held appointments within OSRD or within the British Government and at the same time were connected with commercial firms, would be regarded as dual personalities. Information would be given them in their capacities as Government appointees, with the understanding that it was not available to them as employees of commercial firms. To have excluded such persons from participation in Government research would have seriously crippled the over-all scientific research and development effort. Most of the men who were faced with this dual responsibility no doubt leaned over backward to observe the spirit as well as the letter of the agreement.

Another important point on which agreement was reached was that British research would concern itself principally with immediate objectives connected with the defense of Britain, and that long-range developments should in general be undertaken in the United States. This was considerably modified as the war progressed, good examples being the development by the United States of rockets, the proximity fuze, and microwave radar.

2. THE TRANSITION FROM THE CO-ORDINATION TO THE ADMINISTRATION OF RESEARCH

In the matter of weapons, war has always been a contest between measure and countermeasure. Until World War II nations had customarily entered a new war armed with the weapons, countermeasures, and tactics they used in the last conflict. No major new weapon introduced after a war had started had ever been developed to the limit of its possibilities before that war ended. The tank and the airplane, for example, were first used in World War I, but they were not highly developed during that conflict and they certainly did not greatly influence its final outcome.

A change in this respect became noticeable within a few months after

the outbreak of World War II. It was manifested particularly in a great increase in the vigor and imagination with which all problems of weapon development were attacked. This was largely because the contest between measure and countermeasure had became a race between scientists rather than a competition between professional military men.

During the years following World War I there had been a phenomenal increase in research facilities and in the number of trained scientists in the United States. This greatly increased our capacity for inventing new weapons and for devising countermeasures to old ones. However, a comparison of the expenditures for such research made just before our entry into the war with those made during the war shows that full advantage had not been taken of this potential during the peace years. The approximate figures for the several Federal agencies are as follows:

Principal Federal Agencies engaged in war research	Expenditures for war research and development to nearest million dollars during fiscal years 1940	1944
Army	$ 13,000,000	$ 289,000,000
Navy	14,000,000	168,000,000
NACA	7,000,000	33,000,000
OSRD	None	156,000,000
	$ 34,000,000	$ 646,000,000

Measured in dollars, approximately twenty times as much research and development was done in 1944 as in 1940. Expenditures for such purposes were even smaller during the 1930's than in 1940. Many writers have ascribed the paucity of weapon research and development during the peace period to lack of imagination and initiative on the part of the armed services. The above figures taken by themselves might well lead to this conclusion, and it is fair enough to ask why for example, the Navy could not by the end of 1939 have had in use the weapons and techniques of antisubmarine warfare that were developed later during the war.

It must be admitted that before World War II very few officers of the Army and Navy had any real conception of the new weapon possibilities lying dormant in science. This was especially true of line officers who had no direct responsibility for such matters. Such officers nevertheless often exercised considerable control over the amount of money requested of Congress and over the purposes for which the funds were to be used. Technical officers with a better understanding of what science had to offer might have insisted during the peace years on research programs of greater scope than were actually presented to the Bureau of the Budget and to Congress, but there was no encouragement for a forward looking policy of this kind. Such efforts as were made were often thwarted by higher authority. Even funds that were intended for research were sometimes diverted to other purposes. For example, after much urging on the part of technical officers, an item of $4,000,000 was earmarked in 1939 for the development of the smaller types of Naval vessels such as motor torpedo boats and landing craft.

The program of development was well under way when instructions were received from higher civilian authority to spend practically all of the money so earmarked on building a type of motor torpedo boat that had already gone beyond the experimental stage and should have been built with other funds. This left practically nothing for the development at that time of landing craft for amphibious operations and delayed the construction of such craft later on.

Admitting these shortcomings in vision it would nevertheless be the greatest fallacy to assume that funds could have been obtained in adequate amounts to completely develop during the peace period such weapons as the proximity fuze, microwave radar, the weapons and techniques of antisubmarine warfare—to mention only a few. Government expenditures for weapon research and development during the war exceeded two billion dollars—exclusive of the expenditures on the atomic bomb. For a reason which will be mentioned presently it would have cost even more to have done this work during the inter-war period. It is inconceivable that the country would have tolerated in the years preceding the war anything like the expenditures that were made for this purpose during the war. Those who advance arguments to the contrary surely have little understanding of the workings of democracy in preparing for national defense in time of peace.

It has been suggested that at least the most important items could have been pushed during the peace period. This presented two difficulties—clairvoyance to some degree in selecting the most important items and the fact that the majority of the projects were interdependent. Many items had their roots for example in electronics and were dependent on developments in that field. An advance along the entire front of applied science was therefore necessary in order to get the quickest results in the development of any one weapon or device. It was this broad advance that was largely responsible for the amazing wartime record of bringing so many new weapons into use and in devising effective countermeasures against so many existing weapons.

A factor of even greater importance than unlimited funds in accelerating new weapon development became operative when Hitler marched into Poland in September 1939. In no profession is the superior mind so important as in science. Mere numbers can never make up for lack of first class intellects in scientific research. In peacetime the inducement for men of this caliber to enter Government service had never been great. This had been especially true in the Armed Services. Top-level scientists, particularly those in the colleges were almost to a man uninterested in weapon research. Many during peacetime actively opposed any kind of war research. This general attitude changed radically with the actual outbreak of war in Europe. Emotional urges and the threat to our own country brought practically every scientist into war research of some kind. The impact of the highest level of scientific minds on the problems of modern warfare even more than unlimited funds, great laboratory facilities and the availability of large numbers of scientists spelled much of the difference between the advances made in weapons during the war years and the peace years.

The attack on the democracies in Europe not only drew the best American scientists into weapon research, it also provided such research at a bargain in cost. Many of the top-flight men never went on the Federal payroll at all but were loaned to the Government by their organizations. The rank and file averaged only very modest salaries and there were no clock-watchers or shirkers among them. Normal working hours meant nothing to these men.

In stressing the contribution of top-flight scientists to the war effort it is not the intention to minimize the contribution of rank and file, nor to give the impression that the higher echelons worked in Ivory Towers. Quite the opposite was the case. The pattern for all research and development undertakings was to organize the personnel in teams with each man working in his own special field. This was carried to the point of assigning various parts of some projects to different laboratories even, in order to take advantage of specialization. One of the most effective and revolutionary weapons developed for antisubmarine warfare during this period was the joint product of four laboratories — one Navy, one university and two industrial. By team effort this weapon was invented and developed in less than fifteen months. Under normal conditions it would have taken six or seven years to bring the weapon from the acceptance-of-a-new-idea stage to service use—and at much greater cost. The top-level scientists rendered perhaps their greatest service in providing imagination, planning, leadership and co-ordination for the teams. No new weapon or device can be said to have been even remotely the invention of any one individual.

With the war experience as a background the Coordinator early in 1944 began discussions on ways and means for retaining the interest and co-operation of top-level scientists in weapon research after the war. Weapons and countermeasures had clearly become more decisive as factors in determining the outcome of wars. In the past such factors, in about the order of their importance, had been superior economic resources, superior political and military leadership, superior training of combat personnel with a will to fight, superior morale of the civilian population, and, finally, superior weapons.

Organized civilian science as represented by OSRD and other agencies had unquestionably increased the importance of weapons in determining the outcome of World War II. OSRD, however, was a temporary agency created for the specific purpose of bringing civilian science into the war. The best men in the various branches of science were recruited for a relatively short period of time, in most instances with a minimal disturbance of their regular academic or industrial connections. The pressure of impending war and war itself had made top-level scientists willing to devote their talents to a kind of work that in normal times was uncongenial to them. It was realized by those in the Armed Services who had become closely associated with these men that, once the pressure of war was removed, scientists of this caliber would return to their peacetime activities. The continuation of an OSRD into the peacetime period was therefore out of the question.

Accepting this as a fact, on June 22, 1944 the Secretary of War and the Secretary of the Navy set up a committee headed by Mr. Charles E. Wilson, Vice Chairman of the War Production Board and President of the General Electric Company, to study the question and to recommend a plan for postwar research. The committee consisted of four civilian scientists, four representatives of the War Department and four representatives of the Navy Department.

It assumed that, with the return of peace, the Armed Services would again have to carry the major responsibility for obtaining funds for research on weapons and for the distribution and expenditure of such funds. It therefore adopted as its main objective the preparation of a plan whereby the Armed Services could retain the collaboration of top-level scientists in civil life on all aspects of scientific endeavor that might have a bearing on national security.

The first discussions in the Committee centered around the question of whether legislation should be requested to establish a new Government agency to bring this about, or whether the machinery of the National Academy of Sciences, which had been established originally to assist the Federal Governmental departments in just such matters, should be used. Within the Committee itself objections to using NAS came from those who believed that the Academy was too conservative and was composed too largely of older men who would not be sufficiently progressive to meet all of the requirements of effective collaboration with the Armed Services. Others believed that, because NAS was immediately available, it should be used at least temporarily as a safeguard against possible delays in obtaining appropriate legislation. It seemed especially important to them that, after OSRD went out of business, a working organization should be available to ensure the participation of top-level scientists in research programs related to national security.

After considerable discussion the Committee recommended that NAS be requested to set up an interim Research Board for National Security, and that Congressional approval of an independent agency to incorporate such a Board be obtained. As soon as Congress should act on this request, the Board could be transferred bodily from the National Academy to the agency so created. The Secretary of War and the Secretary of the Navy approved the report of the Committee and in a joint letter of 9 November 1944 requested the National Academy of Sciences to establish the Research Board for National Security. Dr. Frank B. Jewett, the President of NAS, proceeded promptly to appoint a Board of forty members as recommended by the Committee. One half of the members were civilians of distinction in science, engineering, and industry, the other half were officers having the principal technical responsibilities in the War and Navy Departments. So large a number was considered necessary in order to give representation to the various technical activities of the Armed Services and to cover a reasonable cross section of the many fields of science and technology involved in modern warfare. It is significant that all who were invited by Dr. Jewett to serve on the Board accepted.

In order to offset the working handicap of so large a Board, a small Executive Committee of five members —three civilians and two officers from the Armed Services—was provided to administer the activities of the Board. Dr. Karl T. Compton was selected as the first chairman of the Executive Committee. An Executive Secretary, clerical staff, and office space were provided by NAS.

A large number of research projects were immediately submitted by the War and Navy Departments for consideration by the Board. These were mostly long-range research programs not falling under the cognizance of any one activity of the Services and usually of interest to all. Much of the work was expected to be exploratory in character, with a view to the establishment of specific research programs later on. The Board was not restricted to projects submitted to it by the Services, but was expected to initiate programs of its own. Its work was not to be confined to research in the physical sciences, but was to include studies in various fields of human relations: how to insure immediate and effective teamwork between scientists and the Armed Services in any future emergency; how to provide in the Government service the incentives that motivate scientific and technical men; how to provide Federal aid for the education of young scientists; how to handle the security restrictions placed on discussion and publication of scientific work; and how to improve the

relationships between scientists in the laboratory and the operating personnel of the Armed Services in the field.

In order to remain impartial in its supervision of research programs, RBNS was not to operate laboratories of its own, but was to have its research work done by contract with existing organizations. The Wilson Committee recommended, however, that the charter of the Board be made broad enough to permit it to provide any new research facilities that might be found necessary to meet special needs, the operation of such facilities to be turned over to appropriate agencies.

The work undertaken by RBNS was to be financed by funds transferred to NAS from the appropriations of the War and Navy Departments, in accordance with contracts to be entered into between these Departments and NAS. NAS, in turn, was to make specific contracts as requested by RBNS with the organizations or individuals doing the work. NAS was to exercise no control over the purpose for which the funds transferred from the War and Navy Department appropriations were to be spent. Its function, as the housekeeping agency for RBNS, was to do the clerical and administrative work involved in making the contracts and, on appropriate certification, to pay the bills. The employment of scientific and other personnel engaged in the work would be free from Civil Service regulations.

The proposed method of financing the projects was the same in principle as had always been followed by NAS in doing work for the Government. As a matter of policy, the Academy had never received money directly from Congress. In order to preserve its freedom from political control, the Academy desired no change in this policy. During the deliberations of the Wilson Committee, the proposed financial arrangements were discussed with the Director of the Budget and certain of the leaders in Congress, and encountered no opposition. However, when drafts of the proposed contracts were submitted to the General Accounting Office and to the Bureau of the Budget, difficulties began to develop. Objection was raised to the proposed method of financing on the ground that Government control over the expenditure of the funds would be too remote to be satisfactory. It is likely that the influences which from the beginning were hostile to the participation of NAS in the general program helped to mold opposition to the contracts.

In March 1945 President Roosevelt directed the Secretary of War and the Secretary of the Navy not to transfer funds for the use of RBNS for the fiscal year 1946 until a thorough review of the prospective postwar research situation had been made. In June 1945 President Truman, in letters to the Secretaries of War and Navy, indicated that he wished OSRD to continue, and suggested that RBNS be made an advisory body to the War and Navy Departments and to OSRD. These letters halted the placing of contracts by NAS, but studies of certain research programs were continued by the Executive Committee of the Board. The President had designated the Director of War Mobilization and Reconversion as his representative to consider all aspects of postwar research. An unsuccessful effort was made in consultation with that Office to clear up the difficulties over financing RBNS programs. In October 1945 RBNS to all intents and purpose discontinued its activities. In the meantime the Wilson Committee's recommendation for the establishment by statute of an agency for extending Federal support to science was being pushed.

Pending the passage of such legislation the Navy Department made an independent approach to the handling of postwar research. Simultaneously with the deliberations of the Wilson Committee, the Coordinator of Re-

search had been exploring desirable changes in the Navy Department's own organization for carrying on scientific programs after the war. The Coordinator's Office had been highly successful in carrying out the mission for which it had been created by General Order No. 150, but it was really only a temporary device for meeting the Navy's research and development requirements in World War II. It had been established to perform a staff function directly under the Secretary of the Navy and, as such, served admirably in increasing the effectiveness of OSRD and the other civilian scientific organizations that had been mobilized for that war. But any postwar organization of the Navy Department for handling research would have many more problems to solve.

The place of the Naval Research Laboratory in the Naval organization had to be reconsidered, for one thing. Since its establishment in 1923, the Laboratory had been shuttled back and forth several times between the Bureaus and direct control by the Secretary of the Navy. The experience of the war had strengthened the conclusion that the Laboratory could best serve the interests of the Navy as a whole if it remained free of direct control by any one Bureau. Several research activities had been established by OSRD during the war which needed to be continued and would shortly have to be taken over by the Navy Department. The protection of the Government's interest in the vast number of inventions and patents springing from war research conducted with public funds required special attention. There was need for working out policies and procedures concerning inventions made by Naval employees and for handling secrecy matters involved in research. The war had demonstrated also that the Office of the Secretary of the Navy must assume the main responsibility for stimulating and co-ordinating Naval research, for sponsoring and financing important research outside the Government service, and for focusing Naval attention upon all noteworthy research achievements.

All of these considerations pointed to the need after the war for an office directly under the Secretary of the Navy with much broader functions and greater authority than those of the Co-ordinator's Office. An office with Bureau status administering funds appropriated by Congress specifically for research purposes was indicated, but it was decided that it must not encroach on the normal development programs and limited research functions of the Bureaus. Such portion of this concept as did not require legislation was put into effect by an order of the Secretary of the Navy of 19 May 1945, establishing the Office of Research and Inventions, which absorbed the Office of the Coordinator of Research and Development.

Because the plan for establishing a National Science Foundation, such as Dr. Bush had recommended to the President in July 1945, was making slow progress, a bill was introduced in Congress in May 1946 "to establish an Office of Naval Research . . . ; to plan, foster, and encourage scientific research . . . ; to provide within the Department of the Navy a single office, which, by contract and otherwise, shall . . . obtain, coordinate, and make available to . . . the Navy, world-wide scientific information and the necessary services for conducting specialized and imaginative research; to establish a National Research Advisory Committee . . . "

The Act of Congress establishing the Office of Naval Research was approved on August 1, 1946. The charter of this Office is broad enough to permit the support of research in any field that has a bearing on national security. The Office sponsors research in nuclear physics, medicine, physics, chemistry, mathematics, electronics, mechanics and meteorology. Its activities are co-

ordinated with the rest of the Navy and the National Military Establishment in the fields of power, guided missiles, and all aspects of air, surface, and sub-surface warfare. The individual research projects are being done by contract in institutions of many types throughout the country. The programs include much fundamental research and the advanced training of young scientists.

It will be noted that the primary mission of the ONR is in principle the same as that envisaged by the Wilson Committee for the RBNS; namely, to retain the collaboration of top level civilian scientists in all fields of research having a bearing on national security. The mechanism provided for carrying out this mission differs however from that proposed for the RBNS. In one particular it is the same; the work is as a rule being done by contract, just as we planned for the RBNS, rather than in expanded Navy research laboratories and by increased government personnel. Some new Government facilities are however being provided and others are being financed with Government funds, and turned over to civilian organizations for operation.

The Office administers the Naval Research Laboratory, the Special Devices Center for the development of new training equipment, the Underwater Sound Reference Laboratory, and branch offices in a number of cities. It is a question whether an office such as ONR, which is itself engaged in research, can successfully perform the liaison and co-ordinating functions that had been carried on during the war by the Coordinator's Office. A judge with a horse in the race is likely to be suspected of prejudice. Civilian science will probably again be mobilized in some form in the next emergency, even though the exact pattern of OSRD may not be repeated. In the event of such mobilization, liaison and co-ordination with the Armed Services will again become of the greatest importance. The Research and Development Board of the National Military Establishment, being a staff agency, should be in position to perform this function or to determine how it should be done.

The principal preoccupation of the Wilson Committee was how best to keep top-level scientists thinking of war research in times of peace. That question has not yet been put to the test, since world peace as of 1949 has not been restored. The threat of communism has taken the place of actual war in keeping the country, including its scientists, aroused to the necessity of defense readiness.

World War II, particularly the atomic bomb educated the public to the possibilities of science and to the fact that while research costs money, it is a good investment for promoting national security. Legislation to provide Federal support for science through the establishment of a National Science Foundation has so far failed of enactment, but the Military Services, particularly the Office of Naval Research, have stepped in with funds liberally supplied by Congress to give support to research on a broad front not only for weapon development but for basic research as well.

Not all scientists are happy over this situation. Many fear that military control will dominate research to the point where it will not be carried on in the true spirit of science. Many are asking: Should we be thankful that the military stepped in to do a job that we would otherwise have had to leave undone? Is the job being done in a way that can be wholeheartedly endorsed and approved by American scientists? Assuming that funds are now being administered in the true spirit of science, can we expect this policy to continue? Is the primary end of free American science to be national defense? Can this end be served without impairing the promotion of science for

peaceful purposes? Is it proper for military funds to be used for research which has no specific military objective? These are all symptoms of the aversion of many scientists to research having war making for its objective, and as such should not go unheeded in planning for the future.

For the time being, American science is receiving more Federal support for basic research than ever before. While there is much shaking of heads over the possible contamination of science by too much military influence, there is no question that much experience is being gained that will be invaluable in planning for a permanent National Science Foundation.

Official Armed Forces Photograph

A study in perspective. Looking down the 900-ft. middle bay of the huge Machine Shop located at the Mare Island Naval Shipyard, Vallejo, California.

CIRCULAR CYLINDER STRESSES

Mathematical Determination of Stresses in Thin Walled Circular Cylinders with Axial Temperature Gradient Elastic End Restraint*

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Although the theory of thermal stresses in thin tubes is well known, the equations for stress are not readily applicable to most practical problems. This paper is concerned with the elastically restrained cylinder with temperature expressed as a function of the axial length. Relatively simple stress equations may be obtained for the long cylinder with (1) linear thermal gradient, and (2) constant temperature difference between cylinder and end restraint.

* This work done at the Research and Development Dept. of The Elliott Company. Jeannette. Pa.

NOMENCLATURE.

The following nomenclature is used in the paper:

- C Rotational spring constant of elastic restraint
- E Modulus of elasticity of shell
- E' Plate modulus $[E' = E/(1-\nu^2)]$
- h Thickness of shell
- I Moment of inertia of shell per unit circumference $(h^3/12)$
- L Length of shell
- M Bending moment per unit circumference
- N Normal force
- p Uniform load
- R Mean radius of shell
- S Radial thickness of elastic system
- s Distance from center of rotation of flexible system to point of attachment of shell
- T_0 Temperature of elastic restraint
- T Temperature of shell
- V Shear force per unit circumference
- x Axial distance along shell
- y Radial displacement
- α Coefficient of thermal expansion
- β Characteristic of shell $[3(1-\nu^2)]^{1/4}/\sqrt{Rh}$
- ϵ Strain
- θ Slope of deflected shell
- ν Poisson's ratio
- σ Stress
- $\varphi(\beta x)$, $\zeta(\beta x)$, $\psi(\beta x)$, $\theta(\beta x)$ Functions of βx

INTRODUCTION

With the trend toward higher operating temperatures of industrial equipment, it becomes increasingly important to predict thermal stresses. Components of this high-temperature machinery are often cylindrical, as, for example, the hollow shafts and bearing casings of steam and gas turbines. Such parts may frquently be treated as elastically restrained thin cylinders, and thermal gradients approximated by (1) linear gradient or (2) constant temperature difference between cylinder and end restraint.

(1) When heat transfer by convection and/or radiation is considerable, the temperature varies as a hyperbolic function of the axial length. A rigorous stress analysis becomes very cumbersome. Generally, however, conduction predominates, and departure from the linear gradient will be fairly small.

(2) The case of a constant temperature difference between cylinder and attachment is rarely encountered; but its solution is mathematically identical with that for the shell and restraint at uniform temperature, but with different coefficients of expansion.

GENERAL EQUATIONS FOR DEFORMATION OF A THIN-WALLED TUBE.

Consider a section of a thin-walled circular cylindrical shell (Fig. 1) which undergoes a temperature change from T_0 to T. The strain may be written

$$\epsilon = y/R = \alpha (T-T) + \sigma/E$$

The stress σ may be replaced by the load

$$N = h\sigma$$

which is equivalent to a uniform radial loading

$$p = N/R$$

$$\text{or } p = h\sigma/R = hEy/R^2 - hE\alpha (T-T_0)/R$$

Since from beam bending theory

$$p = -E'I\, d^4y/dx^4$$

we may finally write

$$E'I\, d^4y/dx^4 + hEy/R^2 = hE\alpha (T-T_0)/R \qquad (1)$$

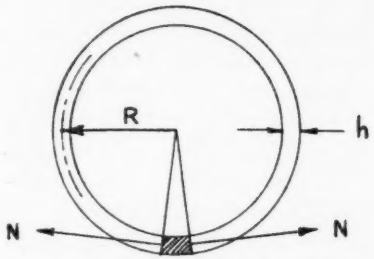

FIG. 1.—Section of a thin-walled circular cylinder.

This equation, which is the expression for the deflection of the beam on elastic foundation, may be integrated whenever the temperature can be expressed as a function of x:

$$y = f(x) + e^{-\beta x}(C_1\cos\beta x + C_2\sin\beta x) + e^{\beta x}(C_3\cos\beta x + C_4\sin\beta x) \quad (2)$$

where

$$\beta = [hE/4E'IR^2]^{1/4} = [3(1-\nu^2)]^{1/4}/\sqrt{Rh}$$

For a long beam, it is necessary that $C_3 = C_4 = 0$, since y would otherwise approach infinity as x approaches infinity. The analysis of the long, or semi-infinite, beam is greatly simplified, and it is profitable to classify all beams as to length.

CLASSIFICATION OF BEAMS.

Several authors (Ref. 1 & 2) have tabulated the functions

$$\varphi(\beta x) = e^{-\beta x}(\cos\beta x + \sin\beta x)$$
$$\zeta(\beta x) = e^{-\beta x}\sin\beta x$$
$$\psi(\beta x) = e^{-\beta x}(\cos\beta x - \sin\beta x)$$
$$\theta(\beta x) = e^{-\beta x}\cos\beta x$$

which are used to describe the deflection of the semi-infinite beam,

$$y = f(x) + e^{-\beta x}(C_1\cos\beta x + C_2\sin\beta x) \quad (3)$$

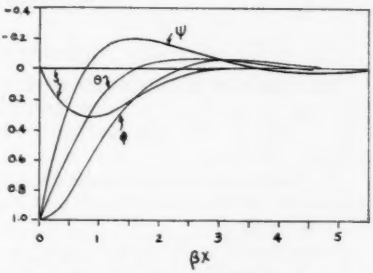

FIG. 2.—Plot of the functions of βx.

Examination of a plot of these functions (Fig. 2) indicates a rapid decrease in amplitude as βx increases, with negligible amplitude at values of βx exceeding π. This means that the beam having $\beta L > \pi$ may be considered semi-infinite (a beam with restraint at one end but extending infinitely in the other direction), since any disturbance originating at one end has become insignificant when the other end is reached. M. Hetényi (Ref. 1) has established the following practical limits for βL:

1. Short beams, and beams of medium length $\beta L < \pi$
2. Long beams $\beta L > \pi$

and advises use of all terms of Eq. (2) when $\beta L < \pi$.

Adjustment of this classification is a matter of judgment.

THE BEAM OF MEDIUM LENGTH.

When beams are of such length that conditions at one end affect the opposite end, all terms of Eq. (2) must be considered. To illustrate the fact that this equation yields cumbersome results, consider a shell with temperature gradient as in Fig. 3. On substitution of

$$T - T_0 = \Delta T(1 - x/L)$$

in Eq. (1) and integrating:

$$y = -R\alpha\Delta T(x-L)/L + e^{-\beta x}[C_1\cos\beta x + C_2\sin\beta x] + e^{\beta x}[C_3\cos\beta x + C_4\sin\beta x]$$

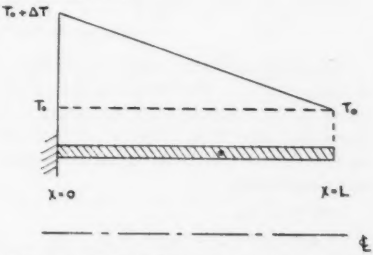

FIG. 3.—Built-in beam of medium length with linear temperature gradient.

$$\theta = -R\alpha\Delta T/L + \beta e^{-\beta x}[(C_2 - C_1)\cos\beta x - (C_2 + C_1)\sin\beta x] + \beta e^{\beta x}[(C_3 + C_4)\cos\beta x + (C_4 - C_3)\sin\beta x]$$

$$+M/E'I = \beta^2 e^{-\beta x}[-2C_2\cos\beta x + 2C_1\sin\beta x] + \beta^2 e^{\beta x}[2C_4\cos\beta x - 2C_3\sin\beta x]$$

$$+V/E'I = \beta^3 e^{-\beta x}[2(C_2 + C_1)\cos\beta x + 2(C_2 - C_1)\sin\beta x] + \beta^3 e^{\beta x}[2(C_4 - C_3)\cos\beta x - 2(C_4 + C_3)\sin\beta x]$$

The end conditions to be used for evaluation of the four constants of integration:

$$\text{At } x = 0 \quad y = R\alpha\Delta T,\ \theta = 0$$
$$\text{At } x = L \quad M = O,\ V = 0$$

are substituted in the above equations to solve for M:

$$M_0 = (-\tanh\beta L)\,(2E'I\beta R\alpha\Delta T/L)\,\frac{\cos\beta L\tanh\beta L[(2\cos\beta L - \sin\beta L)(\cosh\beta L - \sinh\beta L)^2 - \sin\beta L] + [\cosh\beta L - \sinh\beta L]}{\cos\beta L\tanh\beta L[(2\cos\beta L - \sin\beta L)(\cosh\beta L - \sinh\beta L)^2 - \sin\beta L] + [\cosh\beta L - \sinh\beta L]}\,\frac{[(2 + \sin 2\beta L)\cosh\beta L + 2\cos^2\beta L(\cosh\beta L - \sinh\beta L)] - (1 - \tanh\beta L)(2\cos^2\beta L + \sin 2\beta L \operatorname{ctnh}\beta L)}{[(2 + \sin 2\beta L)\cosh\beta L + 2\cos^2\beta L(\cosh\beta L - \sinh\beta L)]}$$

This unwieldly expression reduces, upon the assumption that $\cosh\beta L = \sinh\beta L$, to

$$M_0 = -2E'I\beta R\alpha\Delta T/L$$

THE LONG BEAM.

The remainder of this paper concerns the long, or semi-infinite, beam with (1) linear gradient and (2) constant temperature difference.

(1) Linear temperature variation

substitute $T - T_0 = \Delta T(1 - x/L)$ in Eq. (1) and integrate:

$$y = -R\alpha\Delta T(x - L)/L + C_2\zeta(\beta x) + C_1\theta(\beta x) \quad (3a)$$

$$\theta = -R\alpha\Delta T/L + \beta[C_2\psi(\beta x) - C_1\varphi(\beta x)] \quad (4a)$$

$$M/E'I = 2\beta^2[-C_2\theta(\beta x) + C_1\zeta(\beta x)] \quad (5a)$$

$$V/E'I = 2\beta^3[C_2\varphi(\beta x) + C_1\psi(\beta x)] \quad (6a)$$

when $x = 0$,

$$y_0 = R\alpha\Delta T + C_1 \quad (7a)$$
$$\theta_0 = -R\alpha\Delta T/L + \beta(C_2 - C_1) \quad (8a)$$
$$M_0/E'I = -2\beta^2 C_2 \quad (9a)$$
$$V_0/E'I = 2\beta^3(C_1 + C_2) \quad (10a)$$

(2) Constant temperature difference between shell and end restraint

substitute $T - T_0 = \Delta T$ in Eq. (1) and integrate:

$$y = R\alpha\Delta T + C_1\theta(\beta x) + C_2\zeta(\beta x) \quad (3b)$$

$$\theta = \beta[C_2\psi(\beta x) - C_1\varphi(\beta x)] \quad (4b)$$

$$M/E'I = 2\beta^2[-C_2\theta(\beta x) + C_1\zeta(\beta x)] \quad (5b)$$

$$V/E'I = 2\beta^3[C_2\varphi(\beta x) + C_1\psi(\beta x)] \quad (6b)$$

when $x = 0$,

$$y_0 = R\alpha\Delta T + C_1 \quad (7b)$$
$$\theta_0 = \beta(C_2 - C_1) \quad (8b)$$
$$M_0/E'I = -2\beta^2 C_2 \quad (9b)$$
$$V_0/E'I = 2\beta^3(C_1 + C_2) \quad (10b)$$

The initial boundary conditions necessary for evaluation of C_1 and C_2 will now be found in terms of the physical properties of a restraining system.

LONG BEAM WITH ELASTIC RESTRAINT.

Fig. 4 describes the shell attached to a flexible system; the defining characteristics of the system being the spring constant "C" and lever arm "s". There will be a deflection due to direct radial tension or compression:

$$\text{load} = RV_0$$
$$\sigma = RV_0/2sS = E\epsilon = Ey/R$$
$$y = V_0R^2/2sES$$

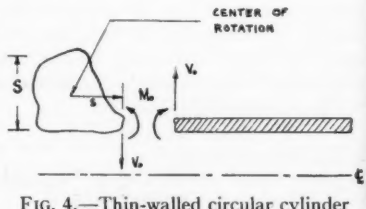

FIG. 4.—Thin-walled circular cylinder attached to flexible system.

However, this deflection is generally very much smaller than that due to rotation of the flexible system, and will be neglected in the subsequent analyses.* It is advisable to check this assumption by noting the magnitude of the direct deflection, using the computed value of V_0 in this check.

Moment M_0 and shear force V_0 will cause the flexible system to rotate through an angle

$$\theta_0 = (M_0 - sV_0)/C \qquad (11)$$

Rotation of the flexible system will cause the point of attachment to translate radially, such that

$$y_0 = R\alpha\Delta T + s\theta_0 \qquad (12)$$

if the flexible system is at $T_0 + \Delta T$, or

$$y_0 = s\theta_0 \qquad (13)$$

if the flexible system is at temperature T_0.

Equations (11), (12), (13), are combined with equations (7), (8), (9), (10) to solve for the constants C_1 and C_2, and for y_0, θ_0, M_0, and V_0. This procedure yields the following dimensionless results:

(1) Linear gradient — flexible system at $T_0 + \Delta T$

$$\frac{-\theta_0}{R\alpha\Delta T/L} = \frac{(2E'I\beta/c)\,(1+s\beta)}{1+(2E'I\beta/c)\,(1+2s\beta+2s^2\beta^2)} \qquad (14a)$$

$$\frac{-M_0}{(2E'I\beta)\,(R\alpha\Delta T/L)} = \frac{1+(2E'I\beta/c)\,(s\beta^2)}{1+(2E'I\beta/c)\,(1+2s\beta+2s^2\beta^2)} \qquad (15a)$$

$$\frac{V_0}{(2E'I\beta^2)\,(R\alpha\Delta T/L)} = \frac{1-(2E'I\beta/c)\,(s\beta)}{1+(2E'I\beta/c)\,(1+2s\beta+2s^2\beta^3)} \qquad (16a)$$

These results are plotted in Figures 5, 6, and 7.

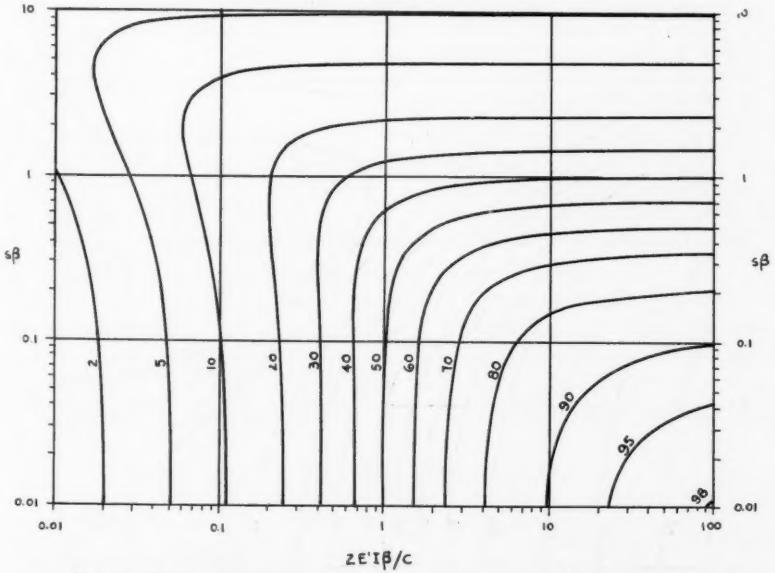

FIG. 5.—Shell with linear gradient. Lines of constant $-\theta_0 L/R\alpha\Delta T$, %.

*With this added parameter it would become necessary to prepare a complete set of curves, such as Fig. 5-9, for each value of direct deflection.

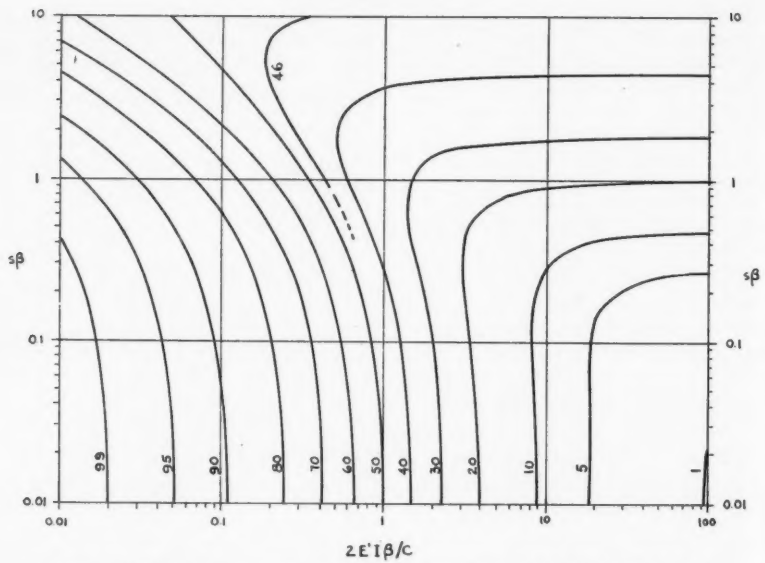

FIG. 6.—Shell with linear gradient. Lines of constant $-M_0L/2E'I\beta R\alpha\Delta T$, %.

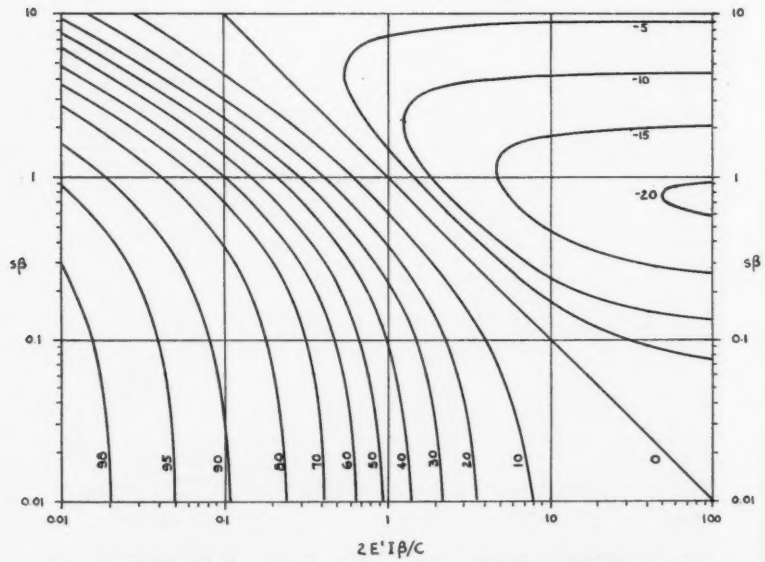

FIG. 7.—Shell with lineargradient. Lines of constant $V_0L/2E'I\beta^2R\alpha\Delta T$, %.
Shell at constant temperature. Lines of constant $M_0/2E'I\beta^2R\alpha\Delta T$, %.

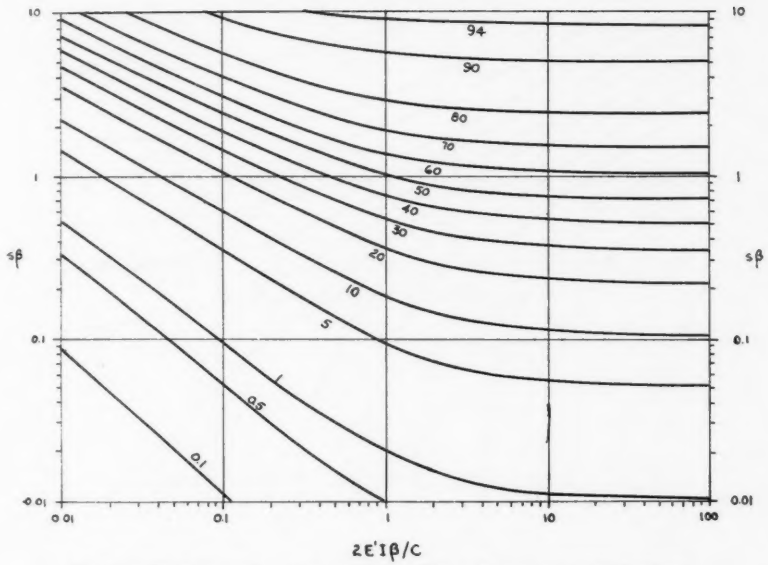

FIG. 8.—Shell at constant temperature. Lines of constant $y_0/R\alpha\Delta T$, %.

(2) Constant Temperature — flexible system at T_0

$$\frac{y_0}{R\alpha\Delta T} = \frac{(2E'I\beta/c)\,(s\beta)\,(1+2s\beta)}{1+(2E'I\beta/c)\,(1+2s\beta+2s^2\beta^2)} \quad (14b)$$

$$\frac{M_0}{(2E'I\beta^2)\,(R\alpha\Delta T)} = \frac{1-(2E'I\beta/c)\,(s\beta)}{1+(2E'I\beta/c)\,(1+2s\beta+2s^2\beta^2)} \quad (15b)$$

$$\frac{-V_0}{(2E'I\beta^3)\,(R\alpha\Delta T)} = \frac{2+(2E'I\beta/c)}{1+(2E'I\beta/c)\,(1+2s\beta+2s^2\beta^2)} \quad (16b)$$

These results are plotted in Figures 7, 8, and 9.

Although these curves are most convenient for rapid calculation of deformations at the point of restraint (and these are usually maximum), they may also be useful to compute deformations at some distance from that point. In that case substitute y_0 and θ_0 into Eq. (7) and (9), and solve for the constants of integration. Then insert the constants into Eq. (3), (4), (5), (6) for stresses at any point:

hoop stress $= Ey/R - E\alpha(T - T_0)$

circumferential bending stress $= 6\nu M/h^2$

total circumferential stress = hoop stress $\pm$ bending stress

longitudinal bending stress $= 6M/h^2$

THE LONG BEAM WITH SPECIAL END ATTACHMENTS $\nu = 0.3$

1. Fixed end—let $C = \infty$

(1) Linear temperature gradient

$$-M_0 = 2E'I\beta R\alpha\Delta T/L = 0.2355\sqrt{Rh^5}E\alpha\Delta T/L$$

$$+V_0 = 2E'I\beta^2 R\alpha\Delta T/L = 0.302\,h^2E\alpha\Delta T/L$$

(2) Constant temperature difference

$$+M_0 = 2E'I\beta^2 R\alpha\Delta T = 0.302\,h^2E\alpha\Delta T$$

$$-V_0 = 4E'I\beta^3 R\alpha\Delta T = 0.777\,h^2E\alpha\Delta T/\sqrt{Rh}$$

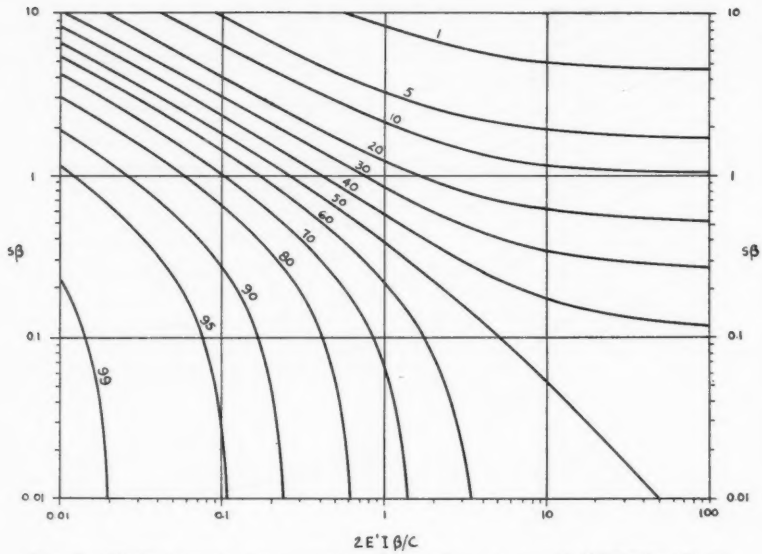

FIG. 9.—Shell at constant temperature. Lines of constant $-V_0/4E'I\beta^3R\alpha\Delta T$, %.

2. Attached to cylinder of same dimensions

(1) Linear temperature gradient
Boundary conditions at $x = 0$:
$\theta_0 = -R\alpha\Delta T/2L$
$V_0 = 0$, since M_0 is a maximum.
Therefore, $y_0 = R\alpha\Delta T(1-1/4\beta L)$
$-M_0 = 2E'I\beta R\alpha\Delta T/4L =$
$0.0589\sqrt{Rh^5}E\alpha\Delta T/L =$
$-M_{0=\infty}/4$

(2) Constant temperature difference
Boundary conditions at $x = 0$:
$y_0 = R\alpha\Delta T/2$
$M_0 = 0$, since θ_0 is a maximum.

Therefore,
$\theta_0 = \beta R\alpha\Delta T/2 = 0.6425\, R\alpha\Delta T/\sqrt{Rh}$
$-V_0 = E'I\beta^3R\alpha\Delta T = 0.194\, h^2 E\alpha\Delta T/\sqrt{Rh} = -V_{c=\infty}/4$

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POWDER METALLURGY

A Symposium on the Art and Practice of Powder Metallurgy

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"Of what significance is powder metallurgy to the Naval Engineer?" This might well be the logical reaction to the presentation of a paper on the subject. In spite of the wide use of powder metallurgy techniques, their principles and applications have not received wide publication and as a result, many engineers have only vague knowledge of the processes employed. It is hoped that this article will serve to clarify the principles of powder metallurgy and indicate some of its more important applications and potentialities.

HISTORICAL

The use of powder metallurgy techniques dates back to 3000 B.C. when the Egyptians made use of it to reduce pure iron oxide in a charcoal fire[1]. The resulting metal sponge was hammered while hot thus welding the iron particles to form ductile iron.

The predecessors of the Incas worked platinum by a powder metallurgy technique similar to that now used in the production of sintered hard carbides. Grains of native platinum were cemented together[2] by an alloy of gold and silver which melted at a lower temperature wetting the platinum and cementing it into a solid shape which could be worked into final form by usual methods.

Wollaston's[3] method of producing malleable platinum, published in 1829, is generally attributed to be the beginning of modern powder metallurgy. His process included the basic steps in use today. Briefly it consisted of the reduction of ammonium chloro-platinate to metallic platinum powder by ignition of the compound. The powder was pressed into a cylinder and compacted by means of a simple mechanical press. The compact was heated in a small coke fired furnace, removed while hot, and struck with a heavy hammer blow. The resulting metal could be worked by ordinary mechanical methods. In 1830 Osann[4] suggested what is now the most widespread application of powder metallurgy. In the course of his work in determining the atomic weight of copper by reduction of the oxide by hydrogen, Osann observed that the reduced copper formed a compact mass. He made a number of observations pertinent to use of powder metals in copying coins and medals which he did by placing powder over the object to be copied, pressed the powder by means of a ring and punch, and sintered it in a split copper box using clay to exclude air. He observed that powders produced at high temperatures did not sinter as well as those produced at lower temperatures, that 20% shrinkage in diameters occurred on sintering but no distortion was found and that the resulting product was harder and stronger than cast copper. He suggested many applications for the process such as making coins and medals initially from powders, printing type, and convex or concave mirrors by metal powders on glass.

BASIC POWDER METALLURGY PROCESSES

The powder metallurgy process for fabricating metals and alloys can be subdivided into four steps:

1. Production and preparation of metal powder
2. Cold forming or pressing
3. Sintering
4. Finishing.

As each step includes numerous variations of methods and conditions, only the more important will be considered in this paper.

POWDER PRODUCTION

Each powder metallurgy technique requires specific procedures and controls which must be held within certain set limits from the first step of powder production to the finished part. In the first step of powder production and preparation for sintering, consideration must be given to chemical composition of the powder, condition of particle surfaces, particle size and size distribution and particle shape. The method of production selected is obviously one which will produce the optimum powder properties required for the production process contemplated. Numerous methods are in use for the production of metal powders for all purposes. Only the more significant utilized for metallurgical grade powdered metals (excluding those used for paint pigments, etc.) will be described.

These methods may be classified according to the basic principle involved in their production. They are:

1. Chemical
2. Mechanical
3. Electrolytic.

Chemical Reduction

Metallic oxides can be reduced by use of hydrogen, and carbon monoxide and other gases. The reduction of copper by hydrogen has previously been mentioned. The reaction is carried on at an elevated temperature below the melting points of both the metal and the compound. In many cases a spongy metallic mass is produced which can be readily crushed and ground to the desired particle size and shape by mechanical means. Other powders prepared by this method include iron, nickel, tungsten, molybdenum and cobalt.

The hydride method may be considered a variation of the hydrogen reduction method since it consists of forming a compound of the metal and hydrogen. The hydride compound is decomposed by thermal means at a temperature below the melting point of the metal. Calcium hydride is used to produce other metal hydrides, the calcium hydride reacting with the metallic oxide to form hydride of the metal. Titanium, zirconium, hafnium, thorium, tantalum, uranium, tungsten, molybdenum, chromium and beryllium have been prepared by this method. Still another chemical method is one in which a metallic compound is reduced by use of molten metals usually alkaline earths. The resulting chemical compound (usually an oxide) can be removed by dissolution or evaporation. Titanium is reduced from its tetrachloride by molten magnesium.

The carbonyl process is extensively used because of its advantages in giving a fine spherical powder product. The principle used is that of forming metal carbonyls and thermally decomposing them to form the metal powder. The process is expensive and is usually applied to nickel carbonyl, Ni (CO), and iron carbonyl, Fe $(CO)_5$ to be used for manufacture of magnetic cores where a fine grained, uniform particle is essential.

Mechanical Methods

Under mechanical methods, machining and milling might be listed as the oldest used. They are most effectively applied to brittle or friable metals and alloys such as antimony, bismuth, beryllium, chromium, manganese, molybdenum, nickel, silicon, etc. and alloys such as aluminum—copper, copper - tin, nickel - iron, nickel - copper, phosphor-copper, etc. Reducing the alloy to the desired particle size is usually accomplished by ball milling. Particle shape and surface conditions may be controlled by variations of milling techniques and media (using non oxidizing liquids, controlling milling atmosphere, etc.). The disadvantages of this method may be listed as (a) possible contamination of the powder by grinding or milling equipment, (b) no refining reactions can take place as in chemical or electrolytic methods and (c) oxidation of particle surfaces is likely. In the category of

granulating or atomizing, shotting is recognized as the fore runner of these processes. The metal is poured through a screen and allowed to fall through a cooling medium of liquid or gas a great enough distance to allow the metal droplets to solidify. Lead shot has been made in this manner for over a century. Granulation is similar in principle but is accomplished by agitating or stirring the molten metal during solidification thus preventing the coalescing of the particles into a solid mass. Oxidation effects are severe and the method can be applied only to metals which are not easily oxidized such as lead, tin, mercury, or their alloys.

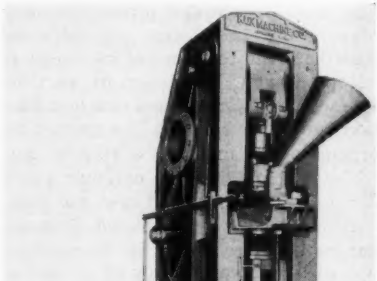
Atomizing is another variation of shotting with the molten metal flowing through a small orifice into a stream of fluid or gas under pressure. The metal is "atomized" into fine particles possessing a "tear drop" shape. Metals prepared by atomizing are those of relatively low melting points (below 1300°F) such as aluminum, lead, tin and zinc. Refinements of the process have been made to control particle size and to prevent oxidation and contamination of particle surfaces.

Electrolytic Methods

The electrolytic method is essentially an electroplating process but, unlike electroplating, is controlled to give a spongy deposit which can be readily stripped from the electrode and reduced to a powder of the desired particle shape and size. Variations of the process include electrolysis of fused salts to produce a deposit of small crystals of a metal or metallic compound. The fused salt method incurs the difficulty of obtaining a salt-free metallic deposit.

PRESSING OF METAL POWDERS

The compacting or molding of metal powders into a desired form preparatory to sintering to a finished metallic part of specified physical properties and dimension is probably the most important step of a powder metallurgy process; since the success of the following sintering process depends largely on the condition and relation of the individual metallic particles of the "green" compact.



Automatic Compacting Press for Preforming Powder Metal Parts Prior to Sintering.
Courtesy of Kux Machine Co., Chicago, Ill.

A brief description of some of the more important considerations in pressing will serve to emphasize this point.

To begin, it might be well to point out that in making a strong metallic part from powders, the process to be used must provide a means of establishing atomic bonds between the particles. In this respect the process might be considered to be analogous to casting a metallic part but with the limitation of having the individual atoms in the solid state. Obviously it is a prime objective to bring the individual particles in close enough contact with each other to be able to establish as strong atomic binding forces as possible between the particles. As compared to casting a liquid metal, the arranging of solid particles to bring them in

close enough contact to allow atomic forces to be effective presents a somewhat more difficult problem. In order to press a compact of sufficient cohesive strength to allow subsequent handling, a number of important factors must be given consideration.

Metallic powders when pressed in a confined cylinder do not behave according to the hydraulic principles which apply to liquids. Particles tend to resist compaction as a result of their "bridging action". A compact after pressing will consequently show greater density at its surfaces than at its center. This effect can be minimized by proper selection of particle shape, size and distribution, powder treatment and control of pressing conditions. For example, plate-shaped particles have been found more difficult to compact than equiaxed - angular shaped particles. Spherical-shaped particles are well suited for uniform filling and packing in a mold, but require high compacting pressures to avoid large variations of density from the outside to the center of the compact.

In any pressing operation the particle surfaces must be clean and free from inhibiting films, oxides or absorbed gases which would prevent a metallic contact from being established. Heat treatments in a reducing atmosphere are commonly used to remove such films. Since the method of powder manufacture determines the size and shape of the particle, as well as its surface condition, methods of treatment and pressing must be chosen to obtain the optimum bonding conditions between the metallic particles.

Selection of die materials and design of dies for pressing metal powders are extremely important to the success of the process. If a hard powder is to be pressed, the die wall will be subject to severe abrasion with high pressures being required to obtain the desired density in the compact. In addition to withstanding the high pressures to be used the die must have good wear resistance in order to maintain dimensional tolerances in pressed compacts. The die plunger must be given enough clearance to allow the escape of gas from the mold cavity but not enough to allow the powder to flow between the plunger and die wall. The die cavity should be large enough to hold the required amount of unpacked powder, usually 2 to 3 times the pressed compact volume. The die is tapered from the ejection side to allow the compacts

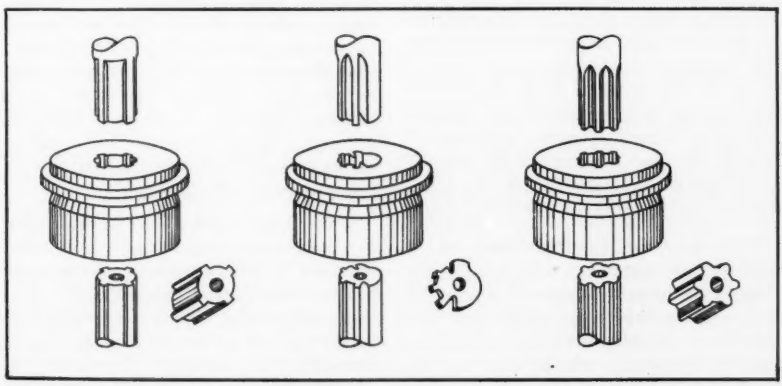


Illustration of Mating Dies and Punches for Compacting Complex Shapes Such as Gears and Cams.

Courtesy of Moraine Products Division General Motors Corp.

to be removed without breakage. The use of a die lubricant is highly desirable to reduce die wear and increase the ease of compact ejection.

Filling of the die, pressing, and ejection of the compact are accomplished automatically in production processes and under such a method the timing of each operation, the rate of punch travel, punch dwell, and compact ejection must be accurately determined and controlled. The precise amount of powder of uniform particle size, shape, and distribution must enter the die cavity, be levelled, pressed and ejected as a finished compact in one cycle of operation. Any variation of the pre-set operation would cause large variations in finished part dimensions, and the resulting "green" pressed compacts might have insufficient strength to prevent them from cracking on ejection from the die or in subsequent handling prior to sintering.

A less common method of compaction is the use of hydraulic pressure in a closed cylinder. The metal powder is placed in an elastic container inside a liquid-filled hydraulic cylinder. The pressure applied to the cylinder is uniformly transmitted to all surfaces of the compact, thus resulting in a more uniformly dense compact. This method is ordinarily applied in processes where the compact is to be sintered and mechanically worked into metal bars which will be fabricated into finished bar stock, sheets, or wire. The method is not used for production of finished parts where intricate forms and close dimensional tolerances are required.

Hot pressing is mentioned as a method of forming metal powders though it includes some elements of sintering in the same operation. The powder is introduced into a heated die, usually graphite, which acts as the electrical resistance heating element. The compacting is done at a relatively high temperature with a limited amount of sintering occuring simultaneously. The degree of sintering is dependent on the temperature and time of pressing. Most hot pressing operations are followed by an additional sintering treatment. The hot pressing technique has the disadvantage of a low production rate and a short die life. Powders are easily oxidized in the process if special precautions are not taken to prevent it.

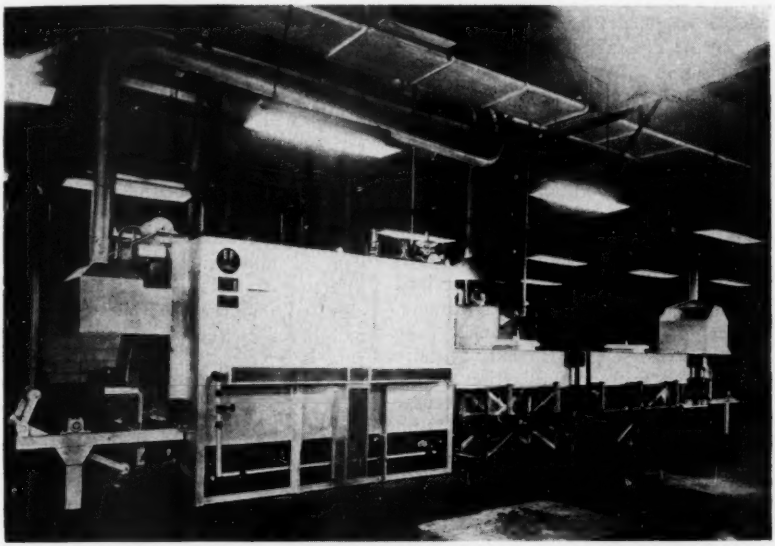
Extrusion is mentioned as a special method of pressing or compacting powder metals. It is employed by the Carboloy Co. to form long parts such as rods, tube, etc. It is used for carbides, refractory materials and welding rods. Extrusion may be done by use of an organic binder with subsequent sintering removing the binder by volatilization. It may be done hot with sintering taking place during extrusion.

SINTERING

The term "sintering" as used in the powder metallurgy industry applies to the process of subjecting the "green" compact to heat under various controls of temperature, atmosphere and time, to cause an optimum bonding of the metal particles to take place.

Wretblad and Wulff[5] have defined sintering more technically as "the process by which solid bodies are bonded by atomic forces". They further state that sintering may take place at room temperature without application of pressure and that soldering, welding, seizing, sticking of metals, and molding of plastics and ceramics fall within the scope of their definition.

The exact mechanism of sintering has not been determined. Numerous theories have been proposed but none has been universally accepted. Each of them deals with the fundamental factors involved in producing the bonds between the particles. Good experimental evidence exists to support the principal theories. However, because of the number of variables in sintering



Continuous Sintering Furnace.
Courtesy of The Electric Furnace Co., Salem, Ohio

the most simple materials under the closest controls, it is not possible to definitely establish any one theory which can be universally applied.

As Alexander, Kisczynski and Dawson[6] have pointed out, a large amount of atomic rearrangement occurs during sintering with at least 6 phenomena that could account for them. They are—

1. Plastic Flow
2. Creep
3. Viscous Flow
4. Volume Diffusion
5. Surface Diffusion
6. Evaporation and Condensation

The authors discussed their experimental work of sintering copper wires to copper plates and concluded that the sintering was a diffusion mechanism up to 1070°C. They also indicated that gold wires exhibit viscous flow at a temperature of 1050°C.

Hausner & Dedrick[7] have concluded that many factors and processes are involved in sintering and that one or more of several processes may determine sintering at the same time. They divide the factors affecting sintering into three groups—

1. Factors characteristic of the material
2. Factors characteristic of the particles
3. Factors characteristic of the processing treatment

The work briefly described above illustrates the complexity of the sintering process. It is typical of the extensive and highly scientific work in the field of physics of powder metallurgy now being conducted to determine the true nature of sintering.

A comparison of pressing and sintering a powdered metal with annealing a solid metal in the cold-worked state may help clarify the conditions of the powder particles during sintering.[8]

When a metal is cold worked within its plastic range, deformation takes place by slip of crystals along certain crystallographic planes. As deformation continues the re-arrangement of crystal lattices tends to retard slip and the crystals become elongated until the familiar fibrous structure is obtained. The "worked" condition is characterized by the changes in physical properties of increased hardness and tensile strength and decreased ductility. When a metal in the deformed state described above is subjected to a heat treatment, a change in structure occurs. The highly stressed grains take a more stable form by recrystallization. If the heat treatment is continued an increase of grain size results. At the point where recrystallization has just been completed and little or no grain growth has occurred, a metal usually exhibits its best properties. At this point the ratio of grain boundary area to grain area is large, and effects of impurities in the grain boundaries as well as effects of orientation are minimized.

This analogy cannot be rigorously applied to sintering but it will serve to illustrate some of the basic factors involved and point out some important differences. A cold pressed or "green" compact may be regarded as analagous to a plastically deformed metal. In pressing the compact the individual particles have been forced close together and to a certain extent have actually been plastically deformed. The weakness of a "green" compact results from the inability of pressing to force more than a very small proportion of the particle surfaces in contact with each other. On heating, the same phenomena of grain growth is observed with powder metals. The diffusion is limited by the surface area in contact. Recrystallization begins at points of contact, then progresses to produce more bonds with adjoining crystals. It is evident that microscopic voids, present in a pressed powder metal compact will not be completely eliminated by ordinary sintering. Surface impurities tend to become segregated in grain boundaries; consequently, a powder metal compact in the as-sintered condition will not exhibit physical properties comparable to those of the "normalized" metal described above.

The fact that sintering is a means of establishing atomic bonds between particles by surface diffusion, should be kept in mind in considering factors affecting sintering. It is conducted at elevated temperatures because atomic mobility is increased and the diffusion rate is accelerated. Inert or reducing atmospheres are used to minimize the effect of surface films in preventing bonding of the particles.

The conditions obtained in actual sintering are greatly complicated by variation in particle size, chemical reactions, entrapped gases, formation of gases, presence of additional metallic phases, the degree of plastic deformation and numerous other factors.

In sintering powder metal compacts it is essential to closely control all the variables possible. Those may be listed as:

1. Atmosphere
2. Rate of heating
3. Sintering temperature
4. Sintering time
5. Rate of cooling.

The accuracy or degree of control required varies with the material being sintered, the purity of the powder, the particle size, shape and distribution, the pressing treatment used, etc.

The sintering atmosphere is extremely important in powder metallurgy processes. The particle surfaces must be protected from oxidation if bonding is to be effective. If a large surface area is exposed to any oxidizing conditions present, a reducing atmosphere may be required to remove oxide films from metals which become quickly oxidized on contact

with air. If a metal powder contains excessively large amounts of absorbed gas a vacuum sintering treatment may be required. Inert atmospheres such as argon are used in special cases.

Though most commercial sintering processes employ gas heating in a continuous moving-grate type furnace, the use of electric heating for sintering is often utilized. Electric furnaces using wire or rod resistance-heating elements are employed where higher sintering temperatures are required, or where special conditions of atmosphere control are necessary. A special method of electric resistance heating with the part being sintered acting as the resistance element is used in the production of the refractory metals, molybdenum, tantalum, and tungsten. Sintering is done in a bell type furnace which is sealed to protect the metal from oxidation by the atmosphere. The schematic diagrams Fig. 1 and Fig. 2 illustrate the two types of sintering equipment.

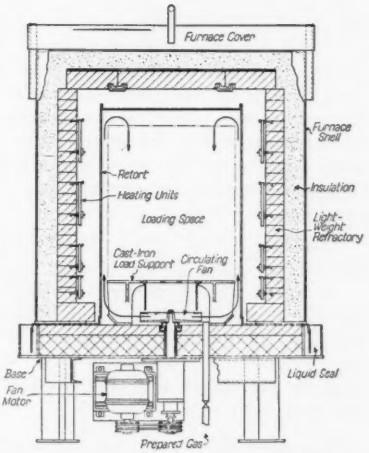


Fig. 2.—Diagrammatic Cross Section of Typical Bell Type of Furnace, Wherein Atmosphere Is Circulated Through Charge by a Fan Below the Load.

Courtesy of the American Society for Metals

In sintering steel compacts, decarburization occurs if the sintering atmosphere is oxidizing. A hydrocarbon gas is partially burned or cracked to produce a reducing atmosphere which will not have a decarburizing effect on the metal particles. A cracked hydrocarbon gas atmosphere is the most commonly used commercial sintering practice. The control of oxygen and moisture in the sintering atmosphere is of utmost importance since small amounts may react with the particle surfaces to cause oxidation or decarburization. The following deleterious reactions can occur during sintering if atmosphere control is inadequate.

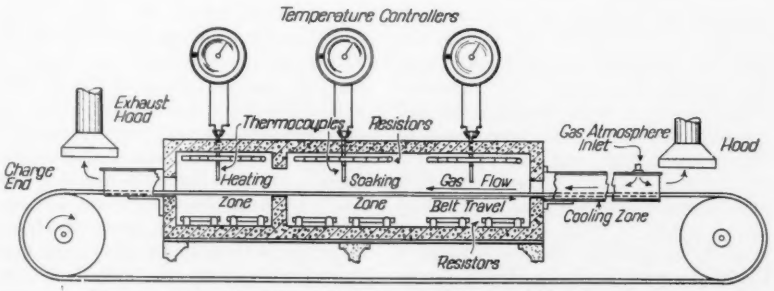


Fig. 1.—Schematic View of Modern Continuous Sintering Furnace.

Courtesy of the American Society for Metals

$2\ H_2O \rightarrow 2H_2 + O_2$

$2\ CO_2 \rightarrow 2CO + O_2$

$H_2O + C \rightarrow H_2 + CO$

Oxide films will react with carbon in steel causing decarburization. Graphite is usually added to the "green" compact to compensate for the loss. Graphite may also be added to reduce oxide films and improve the effectiveness of sintering.

The rate of heating is especially important in materials containing large amounts of absorbed gas and where die lubricants have been used in cold forming. If the heating rate is not closely controlled, "growth" of the compact may occur during the sintering cycle.

In general the sintering temperature for a given material is about ¾ of its melting temperature, with the exception of the refractory metals which are sintered quite close to their melting points. Where sintering of mixed powders is carried out, the sintering temperature may exceed the melting point of the lowest melting phase. This is termed "sintering in the presence of a liquid phase" and is common practice for the porous bronzes and hard carbides, the molten phases being Sn and Co, respectively.

In sintering with a liquid phase the resulting diffusion and shrinkage depend on the liquid-solid solubility relationship of the phases present. For example, in sintering the hard carbides, tungsten carbide plus 7% cobalt, the cobalt is partially soluble in the tungsten carbide, with good particle contacts resulting in a high density sintered compact. Obviously, the percentage of liquid phase must not exceed a fixed limit for any given system, since the molten phase would not be retained by the compact if that limit were exceeded. In general the presence of a liquid phase reduces sintering time and produces a more dense and stronger product.

The question of shrinkage and dimensional tolerance of metal compacts in sintering might well be discussed at this point in connection with the sintering and pressing conditions which affect them. A cold-pressed or "green" compact contains a relatively large proportion of voids or pores. This porosity varies quite widely with particle size, and shape, and compacting pressure. For example, assuming 40% of the volume of a "green pressed" compact to be voids, the compact is said to have a relative apparent density of 60%, by comparing the weight of the compact with the weight of an equal volume of solid metal. On sintering, the compact may be found to have a relative density of 90%, the change in density resulting from the increased attraction of the particles, grain growth, etc. with the consequent closing of voids. The change in volume thus results in shrinkage or a decrease in the linear dimensions of the sintered compact. If uniform shrinkage were obtained the change in dimensions would be proportional to the total change in volume.

Because of the inherent property of powder metals to resist flow on pressing, the density will be found to vary in a cold-pressed powder compact. When the compact is sintered the greatest shrinkage occurs in low density portions. Larger shrinkage will occur in heavy sections or in complicated shapes where die filling is impeded in the pressing operation. Large variations in shrinkage can result in warpage and distortion of the sintered part. Distortion and warpage may be minimized by proper proportioning of powder particle size and shape, correct design of dies for cold pressing and control of sintering conditions. Because greater distortion is more likely in large parts than in smaller ones, most commercial parts are limited in size, with some exceptions, to cross sections of 2 inches in width and 2 inches in

length.[9] By allowing for distortion the following tolerances are commercially feasible on simple round symmetrical parts:

Diameter	Tolerance
½ inch	± 0.0005 inch
¾ inch	± 0.0008 inch
1 inch	± 0.001 inch

Courtesy of "Product Engineering"

The limitations as to part shape include sharp variations in wall thickness, placement of holes, slots, and projections on irregular shaped pieces, etc. Spherical shapes are difficult. In general it may be stated that any shape can be pressed in metal powder that can be hobbed into the tool required for pressing that shape. Holes can be formed only in the direction of pressing while threaded parts can't be handled because they could not be ejected from the mold.

In contrast to the shrinkage of powder metal parts usually observed in sintering, special circumstances sometimes result in an increase in volume or growth. This phenomenon is ordinarily associated with powders pressed at high pressures with a resulting entrapment of gases. On sintering, the entrapped gases cause the compact to expand or grow. Growth can be avoided by gradually bringing the compact to sintering temperature to allow most of the entrapped gas to escape before sintering begins.

POST SINTERING TREATMENTS

The post sintering treatments may be considered as supplements to the conventional powder metallurgy production processes. These treatments are designed to obtain improved properties and close tolerances not possible or practical by simply pressing and sintering as previously described.

The most commonly used process is one of repressing or "coining". "Coining" consists of placing the sintered powder metal part in an accurately sized die and subjecting it to a high pressing pressure to bring the part to precise final tolerances. The coining operation is done at room temperature, often at a pressure more than double that of the original compacting pressure.

Another technique often employed is that of repressing a part hot in a preheated die as it leaves the sintering furnace in order to increase its density and strength. Such an operation is similar to forging and is commonly termed hot forging.

Both processes mentioned serve to overcome the inherent limitations of the powder metallurgy process by accurate sizing and forceably closing voids left after sintering.

INDUSTRIAL APPLICATION OF POWDER METALLURGY PROCESSES

The applications of powder metallurgy processes to industrial production can be attributed to the following factors:

1. Lower production cost
2. Attainment of unique special properties
3. Only process capable of production of special materials.

The more important industrial powder metallurgy products and processes will be briefly described to illustrate industrial applications of powder metallurgy.

STRUCTURAL PARTS

Powder metallurgy techniques are often employed industrially when a manufacturing operation can be simplified and the cost reduced by their adoption. The more important considerations in selecting a powder metallurgy method of manufacture may be listed as follows:

1. Maintaining required tolerance.
2. Required strength of finished part.
3. Rate of production obtainable.
4. Cost of production equipment, presses and dies, and their maintenance.

Some advantages offered by powder metallurgy for structural parts are:

1. Elimination of the multiple operations of casting, machining, drilling, etc.
2. Elimination of assembly of machined parts.
3. High rate of production.
4. Simplification of manufacture.
5. Improved properties.
6. Low scrap loss.

Numerous manufacturers who have adopted powder metallurgy for production of small parts show reductions in cost of production ranging up to 85% over the former method of manufacture. The use of powders for production of structural parts is illustrated by Table I showing properties of typical metal powders.

A comparison of costs of raw materials for various fabricating methods can be obtained from Fig. 3.

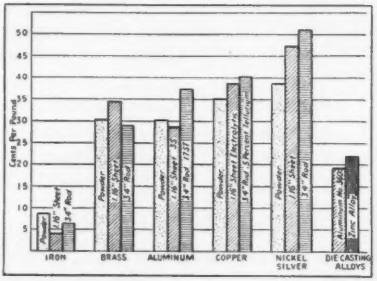


Fig. 3.—Approximate Prices of Metal Powders vs. Rod and Sheet Stock as of February, 1949.

Courtesy of Materials & Methods and the Lionel Corporation.

BEARINGS

In most industrial applications of powder metallurgy with the exception of ordinary structural parts, the objective of using powder metallurgy is to obtain special properties or to work with metals or alloys which can not be produced or fabricated by fusion metallurgy. (Table II.) Copper-lead bearings are a notable example. Copper-lead bearings are superior in strength to cast babbit metal though they are limited to speeds of 3000 r.p.m. and 275°F temperatures. Powder metallurgy is employed in their manufacture because the limited mutual solubility of lead and copper prohibits forming an alloy of over 35% lead by melting.[10]

When the limitations of the 45 Pb—55 Cu bearings were discovered (lack of abrasion and corrosion resistance at higher speeds and temperatures) many attempts were made to overcome the shortcomings by alloying additions. These met with failure because the additive alloy was principally taken up by the copper, giving no protection to the lead. The problem was solved by a

TABLE I.

PROPERTIES OF STRUCTURAL POWDER METAL PARTS.

Powder	Composition %	Flow rate sec/50 gms	Apparent density gms/cc	Cold compressibility	Hardness	Sintering temps. °F	Tensile strength	Ductility % elongation	Sintered density gms/cc	Shrinkage change in length %
Iron	97% Fe min.	30 to 50	2.0 to 2.8	good	.....	1950–2150	20,000–30,000	3–8	6.0–7.0	....
Iron-copper	2 to 11% Cu bal. Fe	.....	.....	fair	.....	1800–2400	30,000–45,000	0.5–2	5.5–6.5	....
Iron-graphite	1% max. graphite bal. Fe	40 to 42	2.5	fair	.....	1900–2200	25,000–40,000	3–6	5.6–6.5	....
Brass	85% Cu 15% Zn	26	3.0	....	.....	1580–1688	37,000	17	.....	0.6
Brass	70% Cu 30% Zn 0.3% P	33	2.6 to 3.0	....	39 Bhn.	1508–1580	36,000	48	.....	1.4
Brass	78.5% Cu 20% Zn 1.5% Pb	30	3.1	....	.....	1580–1652	30,000	12	.....	1.1
"Nickel Silver"	64% Cu 18% Zn 18% Ni	29	3.1	....	88 R_h	1724–1796	44,000	10	.....	1.0

Courtesy of "Materials and Methods" (Manual 52) September 1949

TABLE II.

BEARING MATERIAL REQUIREMENTS.

Requirements for Good Bearing Material	Tin Base Babbitt	Alkali Hardened Lead Base	Cadmium Base 1.35% Nickel	55% Copper 45% Lead
Strength at operating temperature to resist fatigue failure due to pounding	Inadequate	Superior to tin base babbitt	Superior to lead or tin babbitt	OK
Ability to form strong bond to steel backing	Inadequate	Superior to tin base babbitt	Superior to lead or tin babbitt	OK
Sufficient deformability to permit flow at points of insufficient clearance resulting from rod distortion	OK	OK	OK	Inadequate
Sufficient deformability to permit imbedding of dirt and metal particles carried into bearing with oil	OK	OK	OK	Fair
Friction characteristics which will allow contact with shaft at high speeds and load without galling or seizing	OK	OK	OK	Inadequate
Resistance to attack acids by fatty acids present in saponifiable oils or due to oxidation of mineral oils	OK	Very poor	Poor above 250°F	Lead particles attacked*

* Satisfactory up to 3000 R.P.M. on journals 2.5′ diameter. Courtesy of American Society for Metals.

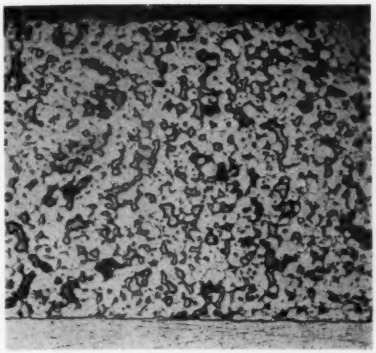
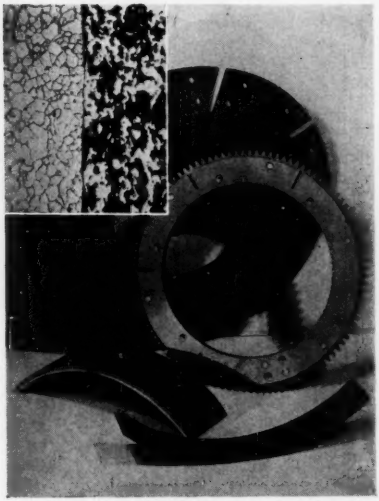


Fig. 4.—Microstructure of Steel-Backed Copper Lead Bearing. (35% Lead, Similar to SAE 480). Magnification 50X.
Courtesy of Federal-Mogul Corporation, Ann Arbor, Michigan

variation of the powder metallurgy technique by sintering a copper-nickel sponge on a steel backing strip at 2000°F. Sintering is carried on only until the particles braze together to form the sponge, and the sponge brazes to the steel. Further sintering is detrimental. The sponge is then impregnated with a lead alloy containing 3% Sn and 3% Sb. to increase its corrosion resistance. The cross section of the bearing (Fig. 4) illustrates the alloy structure. By varying the ratio of Cu-Ni sponge to lead alloy a satisfactory bearing can be produced for all service conditions of high bearing loads and speeds varying from low to extremely high.

FRICTION MATERIALS

Severe service requirements such as brake linings and clutch facings which could not be met by bonded asbestos friction materials were successfully met by powder metallurgy processes, developed commercially by the S. K. Wellman Company of Cleveland, Ohio. The friction material is composed of a mixture of metals and non-metal abrasives selected to give the desired friction characteristics.



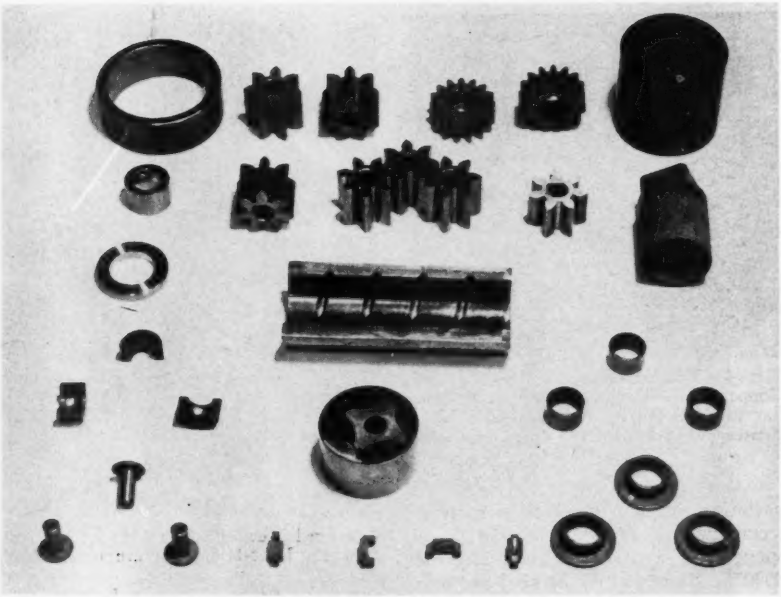
Powdered Metal Facings for Clutches and Brakes. Inset-Microstructure of Backing and Facing.
Courtesy of the S. K. Wellman Co., Cleveland, Ohio

TABLE III—TYPICAL ANALYSES OF FRICTION MATERIALS[11]

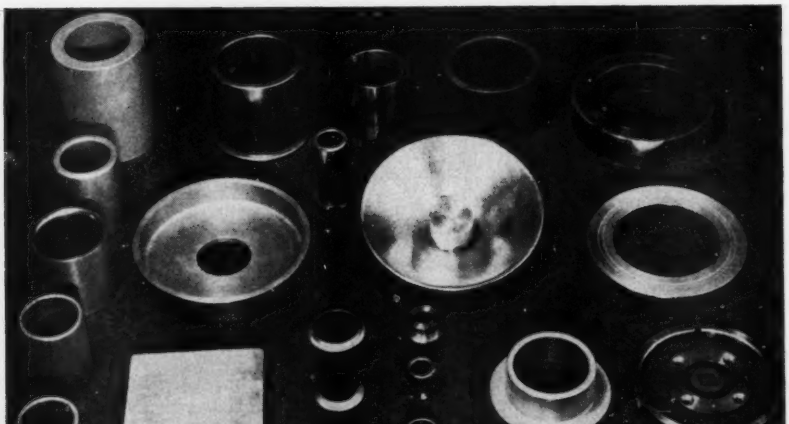
	Clutch and brake disks		Friction Clutches
Cu	73	70.9	62
Fe	—	—	8
Pb	14	10.9	12
Sn	7	6.3	7
Graphite	6	7.4	7
Silica		4.5	4

The alloys employed similar to those in Table III allow smooth engaging and disengaging, maintain strong contact at high loads, and resist heat and wear. The manufacture of metal powder friction parts is briefly outlined as follows:[12]

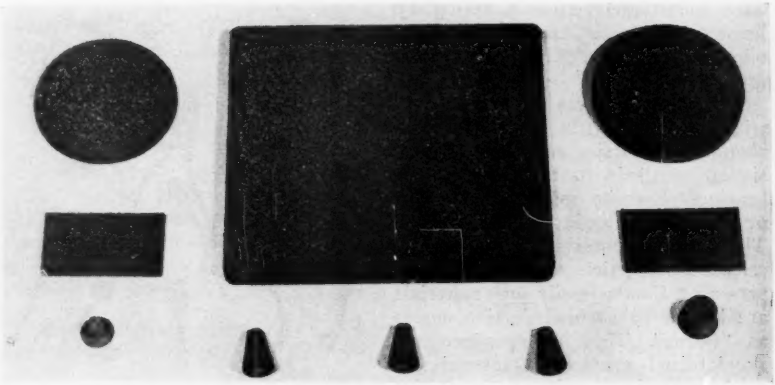
1. Powdered metal friction alloy is pressed at 22,000 to 30,000 p.s.i.
2. The backing, usually low carbon steel, is cleaned and plated with a



Gears and Other Small Structural Parts Made From Iron and Bronze Powders.
Courtesy of Metals Disintegrating Co., Elizabeth, N. J.



Self-Lubricating Bronze Bearings.
Courtesy of Metals Disintegrating Co., Elizabeth, N. J.



Porous Bronze Filters.
Courtesy of Metals Disintegrating Co., Elizabeth, N. J.

0.0001 inch thick coat of nickel or copper.

3. The assembly is placed in a bell type sintering furnace and sintered for 30 to 60 minutes at 1250 to 1650°F. under an applied pressure of 100 to 200 p.s.i. which insures bonding.
4. The part is finished by grinding flat, edge trimming, drilling, grooving, etc.

POROUS PRODUCTS

Porous Bearings:

One of the greatest contributions of the powder metallurgy to industry has been the self-lubricating or porous bearing. In addition to providing lubrication for a moving part during operation it acts as a reservoir for the oil supply. The oil is held by capillary attraction of the pores, a factor which provides accurate regulation of supply of lubricant to the moving part. When rotation begins the resulting temperature rise causes the lubricant to flow, supplying the lubricating film. On cooling the lubricant is reabsorbed into the pores with no dripping or leakage. The disadvantage of porous bearings is their lack of strength resulting from porosity. Higher strength may be obtained at the expense of the amount of contained lubricant (as high as 40% of volume in some bearings) by reducing the amount of porosity. The porous bearing must necessarily be a compromise between the amount of lubrication required and the strength needed to withstand the bearing load. For this reason the most extensive use of these bearings is in small machines, electrical appliances, etc.

Most commonly used powders for porous bearings are bronze (6 to 12% Sn and 0 to 6% graphite) and iron with additions of Pb and graphite. The metal powders are mixed and pressed at pressures between 30,000 and 70,000 p.s.i. depending on the particle sizes and size distribution.[13] Sintering is done in a reducing atmosphere at a temperature of about 1500°F for bronze and 2000°F for iron. Sintering times are short, 20 to 40 minutes, just being long enough to insure a strong bond but not long enough to destroy porosity or cause excessive shrinkage and distortion.

A sizing operation is often necessary to bring the sintered bearing within required tolerances. Oil impregnation is

done immediately after sintering by immersing the porous bearing in hot oil.

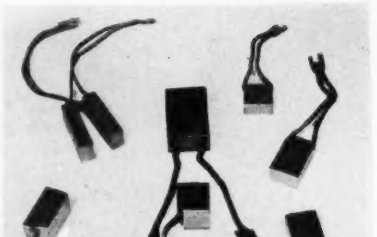
Metal Filters:

Porous metal filters for many industrial applications in petroleum and chemical industries are produced by similar methods to those of porous bearings. Porosity must be continous or interlocking as in porous bearings. The degree of porosity is controlled by selection of particle sizes and pressing pressures. Commercially such materials are known by such distinctive names as "Porex". They are produced in standardized grades in materials of good corrosion resistant properties such as bronze, nickel and stainless steel.

Particle Removal Characteristics of Porex
(Largest dimension of particle removed)

Grade 1	0.002"	to	0.005"
Grade 2	.001"	to	.002"
Grade 3	.0005"	to	.001"
Grade 4	.0001"	to	.0005"

Courtesy Moraine Products Division of General Motors Corporation.

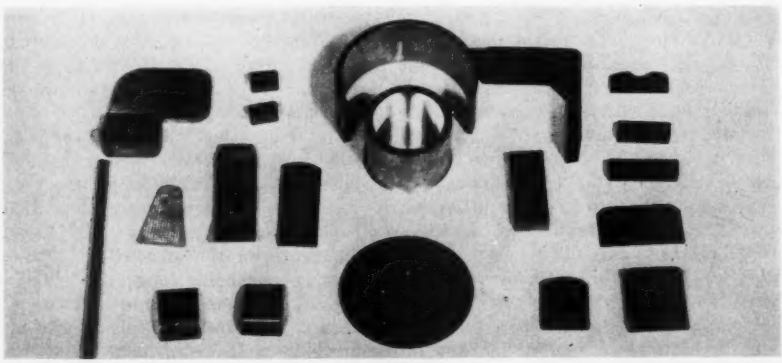


Motor and Generator Brushes Composed of Flake Copper and Graphite Powders.
Courtesy of Metals Disintegrating Co., Elizabeth, N. J.

ELECTRICAL CONTACT MATERIALS

The use of powder metallurgy for electrical contacts allows a combination of properties to be incorporated into the part that cannot be accomplished by alloying. The properties desired are:

1. High electrical conductivity.
2. Low contact resistance.
3. High mechanical strength.
4. High strength and stability at high temperatures.
5. Resistance to wear.
6. Resistance to arcing.



Electrical Contact Materials of Silver-Molybdenum, Silver-Tungsten, and Silver-Nickel-Carbon Alloys.
Courtesy of Metals Disintegrating Co., Elizabeth, N. J.

The development of metal-graphite for brushes and other applications[14] by powder metallurgy followed unsuccessful attempts to emulsify graphite in molten metal. The aim, of course, is to combine high conductivity with low friction and antiwear properties. The powder metallurgy technique consisted of compacting the powder mixtures bronze-graphite and copper-graphite (graphite content of 5 to 70%) and sintering at temperatures between 1350 and 1650°F.

For more severe applications when higher strength and resistance to high temperatures are required, the copper or silver containing bearing, while possessing the desired high conductivity, does not meet the strength and heat resistance demands. The use of tungsten and molybdenum was adopted because the metals were hard, dense, strong, and well suited for high temperature applications. In order to obtain the optimum electrical conductivity they were combined with silver, copper and nickel by the following methods.[15]

1. The tungsten or molybdenum is pressed to shape and sintered into a porous sponge which is infiltrated by dipping into molten copper or silver.

2. The powders such as tungsten and silver are mixed, pressed and presintered at relatively low temperature. The sintered compact is machined to shape and given a final sintering at a higher temperature to give it higher strength and density.

3. The powders are mixed and pressed usually between 40 and 80 tons per square inch. The compact is then sintered to the desired strength and density and formed into the desired part by repressing, forging, extruding, machining, etc.

Some typical contact compositions are 60 Mo - 40 Ag, 80 W - 20 Ag, 82 W - 18 Cu, and W (20 to 80%) - Cu (79 to 19%) plus 1% Ni. The nickel is added to increase density and hardness for added resistance to wear. It should be noted that no alloying takes place between the major components of the contact alloys. If alloying did occur the electrical and physical characteristics would be different and the desirable characteristics lost.

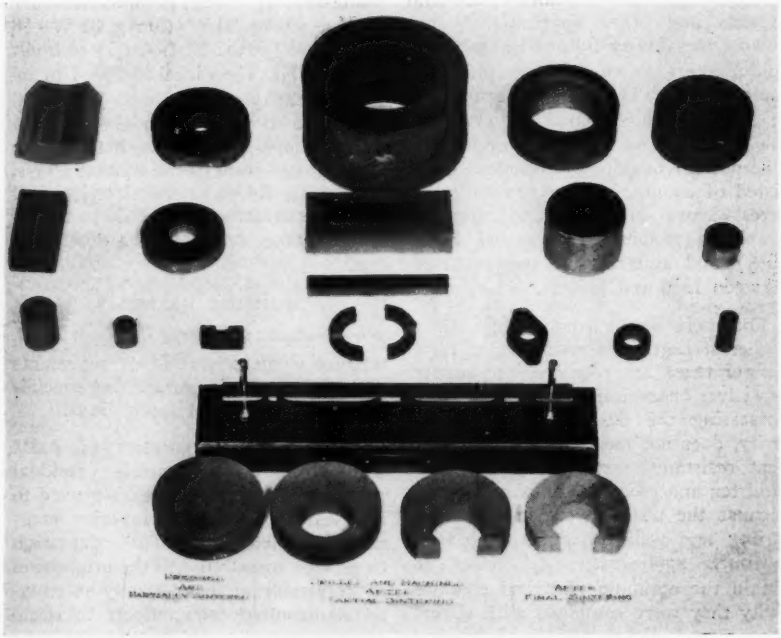
MAGNETIC MATERIALS

The use of powder metallurgy in magnetic materials field represents one of the most important and specialized of its industrial applications.

The inherent properties of parts made from powder metals (residual pores which act as air gaps) proved to be ideal for obtaining superior magnetic characteristics. The adaptation of powder metallurgy to the production of permeable or magnetically soft materials resulted from efforts to overcome excessively high eddy current losses in the solid cores used in telephonic circuits employing high frequencies. It was discovered that such losses could be largely eliminated if the core could be subdivided finely enough.

The use of finely divided electrolytic iron powder was the first in a series of developments which resulted in the discovery of "permalloy", a nickel-iron alloy containing 60 to 90% nickel. The original permalloy was modified by the addition of molybdenum which resulted in a further reduction of eddy current losses and superior magnetic properties.

The process for production of the magnetic powder is described by E. E. Schumacher.[16] The alloy is melted in an electric furnace and cast into ingots which can be hot worked and rolled to thin strip, brittle enough, when



Sintered Alnico Magnets.
Courtesy of Metals Disintegrating Co., Elizabeth, N. J.

cold, to be ground to fine powder. A very small addition of sulfur forms grain boundary film and improved the working properties. The hot rolling must be closely controlled to secure the required grain refinement. The final rolled alloy strip is extremely brittle and can be fractured with very little force. The strip is reduced to powder by crushing, followed by grinding in a ball mill. The powder is classified by screens of 120 to 325 mesh. The powder is annealed to eliminate any residual effects of the working received during the previous processing. The individual particles must then be coated with a ceramic type film to provide insulations between the particles. The thickness of the film must not exceed one half micron.

The cores are then formed by pressing at 200,000 p.s.i. and given a final annealing treatment. The density of the final compact is 7.75 gms/cc compared to 8.65 gms/cc for the cast alloy.

Other important applications for soft magnetic materials are pole pieces for d.c. motors and generators as well as armatures and other similar parts. The powder metallurgy technique eliminates the "hardening" effect of impurities in the cast materials. Most parts are pressed at approximately 30 tons per square inch and sintered in hydrogen at 2500°F from 1 to 3 hours. A coining operation is used for final sizing.

The use of powder metals for permanent magnets is probably the most widely known of the magnetic material applications. The use of

(a) B_i and H_{ci} values are on the basis of intrinsic induction.
Data from the General Electric Company, including demagnetization curves.
Courtesy of Metals Handbook, American Society for Metals

TABLE IV.

NOMINAL PROPERTIES OF CARBON-FREE PERMANENT MAGNET ALLOYS.

Magnet Material	Chemical composition	Form	Hmax, oersteds	Bmax, gausses	Residual B_r	Coercive Force H_c	External Energy (B_dH_d) max	Weight, lb per cu in.	Mechanical Properties	Commercial Methods of Fabrication
Comol Remalloy	12 Co. 17 Mo. rest Fe	Bar Cast	1000	15,200	10,000	225	1,100,000	0.295	Hard, relatively strong, but brittle	Cast, hot, forge machine, punch (thin sections)
Alnico 1	12 Al, 20 Ni 5 Co, rest Fe	Cast	2000	12,350	7,100	400	1,300,000	0.249	Hard, brittle	Cast, grind
Alnico 2 (cast)	10 Al, 17 Ni, 12.5 Co, 6 Cu, rest Fe	Cast	2000	12,600	7,200	540	1,600,000	0.256	Hard, brittle	Cast, grind
Alnico 2 (sintered)	10 Al, 17 Ni, 12.5 Co, 6 Cu, rest Fe	Cast Sintered	2000	12,000	6,900	520	1,430,000	0.245	Hard	Sinter, grind
Alnico 3	12 Al, 25 Ni, rest Fe	Cast	2000	12,000	6,700	450	1,380,000	0.249	Hard, brittle	Cast, grind
Alnico 4	12 Al, 28 Ni, 5 Co, rest Fe	Cast	3000	11,850	5,200	700	1,300,000	0.253	Hard, brittle	Cast, grind
Alnico 5	8 Al, 14 Ni, 24 Co, 3 Cu, rest Fe	Cast	2000	15,700	12,000	575	5,000,000	0.264	Hard, brittle	Cast, grind
Alnico 12	35 Co, 18 Ni, 6 Al, 8 Ti, rest Fe	Cast	3000	12,800	5,800	950	1,750,000	0.260	Hard, brittle	Cast, grind
Cunife	60 Cu, 20 Ni, 20 Fe	Wire	2400	8,400	5,400	550	1,550,000	0.311	Ductile, malleable	Cold roll, machine punch
Cunico	50 Cu, 21 Ni, 29 Co	Strip Rod Wire Cast	3200	8,000	3,400	710	850,000	0.300	Ductile, malleable	Cast, cold roll, machine punch
Vectolite	30 Fe_2O_3, 44 Fe_3O_4, 26 Co_2O_3,	Pressed Pieces	3000	4,800	1,600	900	500,000	0.100	Low strength, brittle	Sinter, grind
Silmanal	86.75 Ag, 8.8 Mn, 4.45 Al	Rod Strip Sheet	20,000	20,830 (a) B_i-830	550	H_{ci} (a) 6000	85,000	0.325	Workable	Machine, punch cold roll

(a) B_i and H_{ci} values are on the basis of intrinsic induction.
Data from the General Electric Company, including demagnetization curves.
Courtesy of Metals Handbook American Society for Metals

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"Alnico" magnets has become so widespread as to almost place it in the category of a household byword. Powder metallurgy techniques were applied for the production of aluminum-nickel-cobalt-iron alloys because the cast alloys exhibited poor casting properties (they have a high surface tension). Cast parts have a large grain size and the alloy is brittle and mechanically weak.

The technique for producing powder has been outlined by G. H. Howe.[17]

A master alloy 50% Fe and 50% Al is melted and the brittle ingot resulting ground to powder by ball milling. The use of the Fe-Al alloy prevents formation of Al_2O_3 which would prevent bonding of the particles in the following sintering operation. The Fe-Al alloy powder is mixed with the other alloy components (Table IV) and pressed at a pressure of 10 tons per square inch or greater. A pre-sintering treatment is used if machining is required for shaping the magnet. It consists of heating for 1 hour in a hydrogen atmosphere furnace at 1100°F followed by rapid cooling. The final sintering is done at a relatively high temperature 2200 to 2400°F, in an atmosphere of pure extremely dry hydrogen. The sintering temperature is above the melting point of the Fe-Al alloy since the sintering must be done in the presence of a liquid phase to insure the complete interdiffusion and alloying necessary to obtain high magnetic properties. Sintering times vary from 1 or 2 hours to 20 hours.

Sintered alnico exhibits the following advantages over the cast alloy:

1. Fine grain structure and superior mechanical strength.
2. Superior average magnetic properties.
3. Close dimensional tolerances.
4. Can be machined without breakage or cracking.

Properties and compositions of several permanent magnet alloys are given in Tables IV and V.

TABLE V.

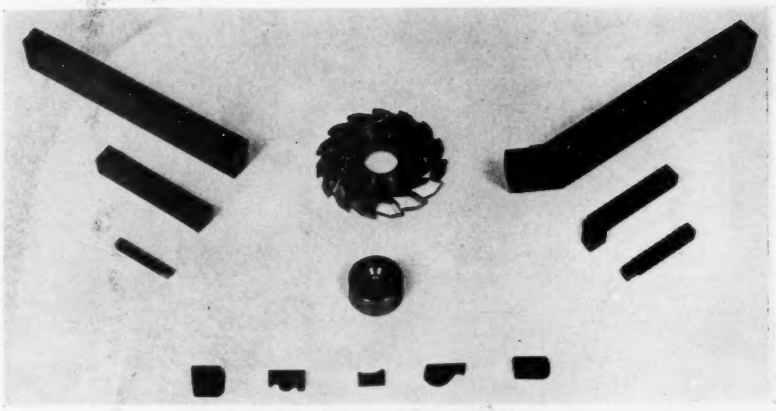
MAGNETIC PROPERTIES OF VARIOUS ALLOYS.

Material (a)	Initial Permeability	Maximum Permeability	Hysteresis Loss, ergs per cu cm per cycle (b)	Residual Induction, gauss	Coercive Force oersteds	Saturation Value gausses (c)	Resistivity, microhm-cm
Ingot iron	250	7,000	5000	13,000	1.0	21,600	11
4% Si iron	600	6,000	3500	12,000	0.5	20,000	50
78.5 Permalloy, quenched	10,000	105,000	200	6,000	0.05	10,700	16
45 Permalloy	2,700	23,000	1200	8,000	0.3	16,000	45
3.8–78.5 Cr-Permalloy	12,000	62,000	200	4,500	0.05	8,000	65
3.8–78.5 Mo-Permalloy	20,000	75,000	200	5,000	0.05	8,500	55
5–79 Mo-Supermalloy	100,000	800,000	20 (d)	6,000 (d)	0.004	8,000	60
45–25 Perminvar, baked	400	2,000	2500	3,000	1.2	15,500	19
7–45–25 Mo-Perminvar, baked	550	3,700	2600	4,300	0.65	10,300	80
70–7.5 Perminvar, annealed	750	3,500	....	.....	0.8	12,000	16

(a) Single numbers preceding the word "Permalloy" indicate the nickel content, and double numbers signify first the content of chromium or molybdenum, and second, the nickel content. The remainder is iron in each alloy. The two high numbers before "Perminvar" indicate the nickel and cobalt contents, respectively, and the small initial number indicates the molybdenum content. These alloys have constant permeability up to a certain value of H.

(b) For saturation value of the flux density. (c) Saturation value of the intrinsic induction. (d) Approximate value.

Courtesy of Metals Handbook American Society for Metals



Hard Carbide Cutting Tools.
Courtesy of Metals Disintegrating Co. and The Carbaloy Co.

(b) For saturation value of the flux density. (c) Saturation value of the intrinsic induction. (d) Approximate value.
Courtesy of Metals Handbook American Society for Metals

CUTTING TOOLS

Hard Metals:

With the advance of the machine age and the ever-increasing demand for greater production, there has been an accompanying urgent requirement for machine tools capable of higher and higher working speeds. To meet the needs of high speed machining, there has been a continual search for hard, strong materials capable of long economical service under the most exacting requirements.

Tool steels were followed by the Stellites which in turn were followed by the cemented carbides as the most efficient cutting tools. The cemented carbides or hard metals, are made up of the intermetallic compounds, tungsten and carbon, titanium and carbon, and tantalum and carbon. These compounds are characterized by extreme hardness and brittleness. The hardness of the carbides on Mohs Hardness Scale is about 9, compared to diamond, 10 and topaz, 8.

The carbides cannot be cast or sintered into parts without extreme brittleness resulting. They must depend on the addition of a binding material which will provide a strong and relatively ductile bond between the carbide particles. Cobalt is almost universally used because of its unique properties, though nickel is sometimes used to cement tantalum carbide.

The mechanism of binding carbides with cobalt has been studied by numerous investigators[18] who have established the formation of a liquid phase of WC and Co below the melting point of cobalt. The melting point depression results from the solution of WC in Co. On cooling dissolved WC is precipitated and deposited on the undissolved WC.

A similar reaction occurs in the sintering of WC-TiC-Co materials. Carbides are dissolved by the cobalt and redeposited on the undissolved carbide particles on cooling as a solid solution of WC and TiC. These phenomena enable the attainment of a high density part as well as a strong bond between the hard carbide particles.

In the manufacturing process tungsten carbide powder is mixed with lamp black and fired at 2500° to 2700°F for about two hours.[19]

Typical Molybdenum Products. Rolled Sheet, section of Tube, and an Ingot. Ingot Weight 150 Pounds.
Courtesy of Westinghouse Electric Corp., Bloomfield, N. J.

Tantalum and Titanium carbides are made similarly but heating with carbon is carried out at higher temperatures (about 3000°F).

The next step includes milling the carbide powder and mixing it with the binder (cobalt powder). 0.5 to 2% stearic acid is added for lubrication and the mixture cold pressed at a pressure of 5 to 30 tons per square inch. Only simple forms can be pressed because of the powder's extreme resistance to flow during pressing. Sintering is carried on in a hydrogen atmosphere to prevent decarburization or oxidation at a temperature of 2450° to 2725°F. Shrinkages of 12% to 20% occur and must be uniform to obtain sound materials. Presence of certain impurities will cause serious defects and loss of strength in the finished material.

Hot pressing, previously mentioned, is commonly employed in the production of sintered carbides. The powder is placed in an enclosed graphite mold. The mold and powder are heated, usually electrically, to the sintering temperature while under a pressure of 400 to 2500 p.s.i. applied by a press. Pressing, sintering, and sizing are thereby accomplished in one operation with a strong dense part resulting. The disadvantages of the method are short

Courtesy of American Society for Metals

TABLE VI.

PHYSICAL PROPERTIES OF SOME COMMERCIAL CEMENTED CARBIDE COMPOSITIONS (*a*)

Composition	Density g./cc.	Rockwell Hardness, A Scale	Transverse Rupture, Psi.	Young's Modulus, Psi × 10^6 (*b*)	Compressive Strength Psi. (*c*)	Proportional Limit in Compression Psi. (*d*)	Impact Strength Ft-lb. (*e*)	Endurance Limit Psi. (*f*)	Coefficient of Thermal Expansion (*g*)
97% WC, 3% Co	15.25	92.7	170,000	97.5	815,000	780,000	...	.....	.....
95.5% WC, 4.5% Co	15.05	92.3	200,000	90.5	890,000	740,000	....	.....	.....
94% WC, 6% Co	14.85	90 to 92	225,000	88	750,000	600,000	0.73	95,000	5.0 × 10^{-6}
91% WC, 9% Co	14.60	89.5 to 91.5	275,000	..	685,000	540,000	....	.....	.....
87% WC, 13% Co	14.15	87.5 to 90	300,000	80	625,000	525,000	1.10	105,000	5.9 × 10^{-6}
80% WC, 20% Co	13.55	85 to 87	350,000	..	550,000	425,000	1.75	.....	.....
Predominantly WC, with TaC and 13% Co	13.90	87 to 88	275,000	..	610,000	475,000	....	.....	7.25 × 10^{-6}
Predominantly WC, with TaC and 6% Co	14.70	91 to 92	220,000	..	752,000	670,000	0.65	85,000	.....
Predominantly WC, with TiC and 6% Co	11.20	92 to 93	160,000	..	700,000	.....	0.40	90,000	6.8 × 10^{-6}
Predominantly WC, with less TiC than above, 8% Co	12.80	91.5 to 92.5	250,000	..	570,000	560,000	0.60	90,000	.....
Predominantly WC, larger amount of TiC, 7% Co	9.00	92 to 93	150,000	..	725,000	.....	....	.....	7.0 × 10^{-6}
Predominantly WC, with TaC and TiC, 8% Co	11.7	91.5 to 92.5	165,000	72	720,000	.....	....	.....	6.75 × 10^{-6}
Predominantly WC, with TaC and TiC, 11% Co	11.6	90.5 to 91.5	175,000	..	680,000	.....	0.60	85,000	6.0 × 10^{-6}
Predominantly WC, with TaC and TiC, 15% Co	11.4	89.5 to 90.5	190,000	67	670,000	.....	0.92	.....	7.5 × 10^{-6}

NOTES: (*a*) The values given in this table are representative of properties obtained in good production practice. They are not necessarily the highest obtainable, nor do they represent the lowest which are of practical use.

(*b*) Most values for Young's modulus were obtained by W. H. Davenport of the Norton Co. by the musical pitch method.

(*c*) Most of the values for compressive strengths are given through the courtesy of P. W. Bridgman of Harvard University.

(*d*) Proportional limit in compression is the load per unit area at which the increase in strain ceases to be directly proportional to the increase in stress.

(*e*) Impact values are from unnotched specimens approximately ¼-in. square section; Charpy machine was used.

(*f*) Values for endurance limits are based on 20,000,000 cycles, for specimens of R. R. Moore rotating beam type.

(*g*) Average coefficient of expansion per °C. for the range 20 to 700° C. (68 to 1290° F.).

Courtesy of American Society for Metals

die life and a relatively low rate of production per unit equipment.

A third method of forming cemented carbides is an extrusion method. The carbide and binder powders are mixed with an organic binder and extruded through a die. The extruded material is then sintered in the conventional manner. The method is highly advantageous for long parts which cannot be pressed in a die.

Table VI gives physical properties of some commercial cemented carbide compositions.[20]

The use of carbide cutting tools is widespread and their advantages well known. A classification of their application is given in Table VII.[21] The carbide cutting tips are usually attached to a steel shank or other type tool by brazing with a silver brazing alloy fusing about 1300 to 1500°F.

In addition to cutting tools the exceptional properties of carbides have led to their use as metal working dies and tools. They are widely used for wire drawing dies where they give the advantages of:[21]

1. Many times longer life.
2. Closer tolerance in product.
3. Better finish.
4. Increased drawing speed.

Many metal products such as bars, tubes, and shapes, previously requiring machining can be drawn accurately by means of carbide dies. The use of carbide dies for blanking, piercing, forming, and deep drawing of all kinds is being constantly increased. Other special applications where wear resistance is paramount are centerless grinding rests, crimping rolls, rests for thread rollers, collets, stops on automatic screw machines, rivet spinners, burnishing bars, beading rolls, guide rings for textile machines, etc.

TABLE VIIa.

APPLICATIONS.

C-1	Roughing cuts—cast iron and nonferrous.
C-2	General purpose—cast iron and nonferrous.
C-3	Light finishing—cast iron and nonferrous.
C-4	Precision boring—cast iron and nonferrous.
C-5	Roughing cuts—steel.
C-6	General purpose—steel.
C-7	Finishing cuts—steel.
C-8	Precision boring—steel.
C-9	Wear surfaces—no shock.
C-10	Wear surfaces—light shock.
C-11	Wear surfaces—medium shock.
C-12	Wear surfaces—heavy shock.
C-13	Impact service—light.
C-14	Impact service—medium.
C-15	Impact service—heavy.
C-16	Impact service—extra heavy.

The use of cemented carbides at high temperatures in gas turbines is under consideration. Carbide blades have been successfully run in a gas turbine service test at 2000°F. The high temperature strength of these materials is excellent but unfortunately their resistance to oxidation prevents their adoption until a means of protecting them has been perfected.

REFRACTORY METALS

Refractory metals have been so termed because of their extremely high melting points and ability to maintain strength at very high temperatures. Their commercial development has been directly tied to the incandescent lamp industry, with a subsequent emphasis being provided by the electron tube industry.

The intensive search for a lamp filament to overcome the deficiencies of carbon resulted in the introduction of osmium filaments in 1898. This was followed by tantalum which was widely used from 1903 to 1911. Tungsten was introduced in 1904 and gradually supplanted all other materials to become the standard filament material.[22]

TABLE VII.

CLASSIFICATION OF SINTERED CARBIDES.

Manufacturer's or Producer's Recommendation for Standard Grades

	Carboloy	Carmet	Firthite	Kennametal	Talide	Teco	Vas. Ramet	Wesson	Willey
C-1	44A	CA 3	H	K-6	C-88 & C-89	A	2A68	GS	E-8
C-2	883	CA 4	HA	K-6	C-89 & C-91	A-1	2A5	GI	E-6
C-3	905	CA 7	HE	K-8	C-91 & C-93	469	2A7	GA	E-5
C-4	999	CA 8	HF	K-8	C-93	982	2A9	GF	E-3
C-5	78C	CA 5	T-83	K2S	S-88	CHD	EE	WS	710
C-6	78B	CA 1	TA	KM	S-90	C	EM	WM	710
C-7	78	CA 2	T-16	K3H	S-92	CF	E	WH	606
C-8	831	CA 6	T-31	K5H	S-92	CF	EH	—	509
C-9	883	CA 4	T-41	KE5 K138 KE7 K501 K6 K12	C-89	A-1	2A5	—	—
C-10	44A	CA 3	H	—	C-88	A	—	—	—
C-11	55A	—	HC	—	C-8815	B	—	—	E-12
C-12	—	—	T-32	—	C-8020	982	—	—	—
C-13	—	CA 12	DC-1	—	C-88	B	—	—	—
C-14	55A 55B 190	CA 10	DC-2	K-18 K-25	C-8815	B	2A3 2A15 2A20	—	E-25
C-15	—	CA 11	DC-3	—	C-8020	TH	—	—	—
C-16	—	CA 20	DC-4	—	C-7525	TH	—	—	E-25

NOTE: This chart presents the manufacturer's recommendations for carbides for the uses indicated. Classifications from C-9 through C-16 are in the formative stage and should be accepted as tentative only.

Courtesy of "Materials and Methods"

The principle refractory metals and their properties are listed in Table VIII. Commercially the most important of this group are tungsten, molybdenum and tantalum. Titanium and zirconium have gained increased attention recently, and show promise of becoming important structural materials where exceptional corrosion resistance is required.

As stated before, the development of tungsten, and perhaps even the present powder metallurgy industry can be credited to the lamp industry. The basic process for production of tungsten wire was largely a result of the work of W. D. Coolidge of the General Electric Company. Present day production processes are only slightly modified versions of the method he introduced in 1904.

The process begins with tungsten metal powder, reduced from the oxide (wolframite or scheelite) in dry hydrogen at a temperature of about 1600°F.[23] The reduced metal powder is cold pressed into bars at pressure of about 25 tons per square inch. This is done in a split die to allow the removal of the fragile bar without breakage. The bar is immediately pre-sintered in hydrogen at 1800-2200°F for a short time to give it enough strength to permit handling. Sintering takes place in a bell jar in a hydrogen atmosphere by passing an electric current through the bar itself. Sintering time is usually 15 to 30 minutes at temperatures approaching a maximum of 5400°F (melting point of tungsten 6200°F). A shrinkage of 15% occurs on sintering. The sintered rod is preheated to 2900°F and swaged in a high speed swaging machine. The reduction is continued using successively smaller swaging hammers until a fine rod as small as one millimeter in diameter is obtained. In the swaging process the density of the metal is increased from 18 gms/cc to 18.5 gms/cc. The bar is drawn to wire in carbide or diamond dies. Drawing is begun at a temperature of about 1500°F and finished at about 750°F. When drawn to small diameters the wire has a specific gravity closely approaching the theoretical value of 19.3 gms/cc. Its tensile strength is 850,000 p.s.i. If a wire could be drawn to the diameter of one atom, that wire would have a tensile strength of 12,000,000 p.s.i.

Tungsten and molybdenum exhibit rather unusual properties when compared to ordinary metals. They are both brittle at room temperature and show an intercrystalline fracture when in the sintered condition. Unlike the common steels they become more ductile with cold work. This difference is less remarkable when the melting points are considered. The fact that common metals exhibit brittle behavior at sub zero temperatures may be logically compared to the brittle behavior of the refractory metals at room temperature. The increase in ductility produced by cold work may be attributed to a change in grain structure which lowers the cold brittleness range. A similar phenomenon is observed in the lowering of the transition temperature to brittle failure of ship plate steel by the grain refinement produced by normalizing.

The production of molybdenum closely follows the technique used for tungsten. Molybdenum powder is produced from the oxide MoO_3 by hydrogen reduction. Sintering is carried on in hydrogen atmosphere at about 4250°F (melting point 4760°F). Swaging is performed at about 3000°F. Molybdenum finds its major use in the electron tube industry for anodes, grids, plates, etc. because its high ductility allows forming of sheet to the intricate parts required. Another wide use is for electric furnace resistance heating elements. These elements permit furnace temperatures as high as 3600°F.

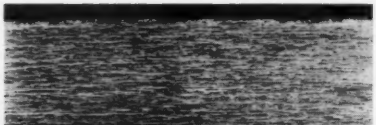
TABLE VIII.

PROPERTIES OF REFRACTORY METALS.

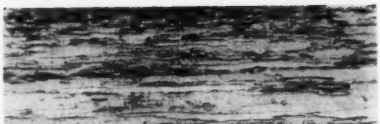
Metal	Crystal System	Approx. Melting Point °F	Density Gms/cc	Tensile Strength Psi × 10^3	Conditions	Elong. %	Harndess Number
Tungsten	BCC	6170	19.3	250–600	wire—hard drawn	1–4	350
				150	wire annealed	0	...
Tantalum	BCC	5425	16.6	50–170	wire—hard drawn	1–2	45–350
				50	wire annealed	25–40	...
Osmium	HCP	4900	22.5	...	cast	...	V-350
				...	.....	...	...
Molybdenum	BCC	4760	10.2	200–350	wire—hard drawn	2–5	140–185
				171	wire annealed	10–25	...
Columbium	BCC	4380	8.57	...	.....	...	75
				...	.....	...	...
Titanium	HCP	3300	4.54	125 (1)	sheet 50% cold rolled	12	R_a64
				80	sheet annealed	25	R_a60
Vanadium	BCC	3150	6.0	...	.....	...	...
						...	...
Zirconium	HCP	3200	6.5	70–90 (2)	sheet—hot rolled followed by cold rolling	9–15	...
						...	...
Uranium	ORTH.	2065	18.9	...	fused	...	R_b93
					cold worked	...	R_b112

BCC—Body centered cubic.
HCP—Hexagonal close packed.
ORTH.—Orthorhombic.
Hardness—Brinell unless otherwise indicated. V—Vickers. R—Rockwell.

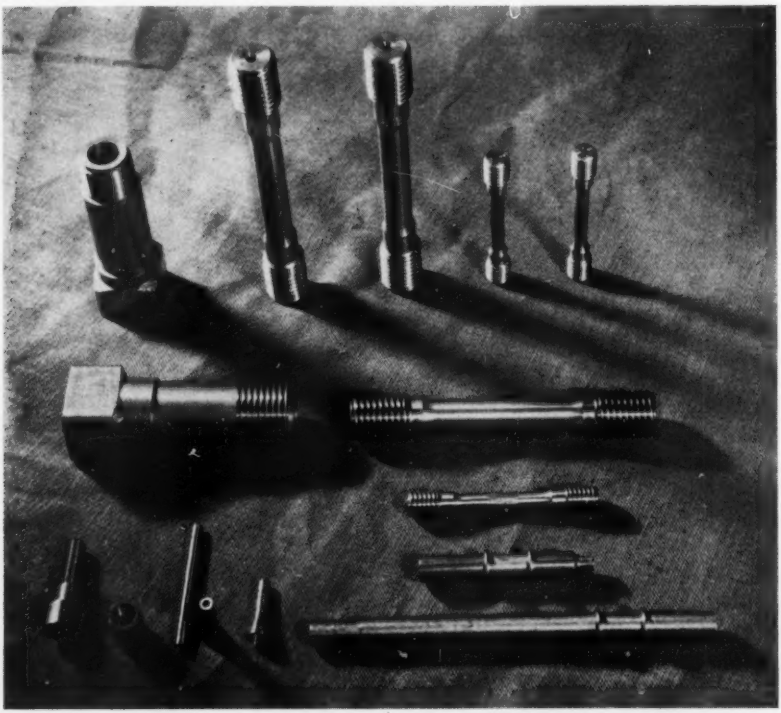
[1] "Titanium Metal" DuPont DeNemours and Co. (Inc.)
[2] US Naval Eng. Exp. Station Data.
Data Source—Metals Handbook-1948
Am. Soc. for Metals
Mechanical Properties of Metals and Alloys-US Dep't Commerce, Nat'l Bureau of Stds.
Circular C-447



Microstructure of Drawn Tungsten Wire. Magnification 500X.
Courtesy of Westinghouse Electric Corporation, Bloomfield, N. J.



Microstructure of Swaged Tungsten Rod. Magnification 500X.
Courtesy of Westinghouse Electric Corporation, Bloomfield, N. J.



Intricate Machined Sections of Pure Molybdenum.
Courtesy of Westinghouse Electric Corp., Bloomfield, N. J.

Tantalum is produced by a method similar to that for tungsten and molybdenum. Sintering must be carried on in a high vacuum because of the metal's property of absorbing large amounts of hydrogen, with embrittlement resulting. Sintering temperatures are about 4800°F. Tantalum exhibits higher ductility than tungsten and molybdenum, has high oxidation resistance, is not attacked by most acids, and is easily welded.

Titanium is mentioned even though production by fusion techniques seems to be preferred to the powder metallurgy method at the present time. Powder metallurgy was largely responsible for development of this metal to its present stage. Titanium powder is produced by the reduction of titanium tetrachloride by molten magnesium. The powder is compressed at fifty tons per square inch, and sintered in a vacuum for 16 hours at a temperature of about 1830°F. A new method developed by the Bureau of Mines[24] consists of enclosing the powders in a metal sheath and hot working the assembly above the recrystallization temperature. The sheath can be readily stripped from the titanium metal which exhibits properties equivalent to those obtained by previous techniques. Titanium has shown exceptional resistance to sea water corrosion, and has approximately half the weight of steel. Its alloys have shown tensile strengths as high as 180,000 p.s.i. and yield strengths as high as 160,000 p.s.i.

Zirconium is prepared similarly to titanium.

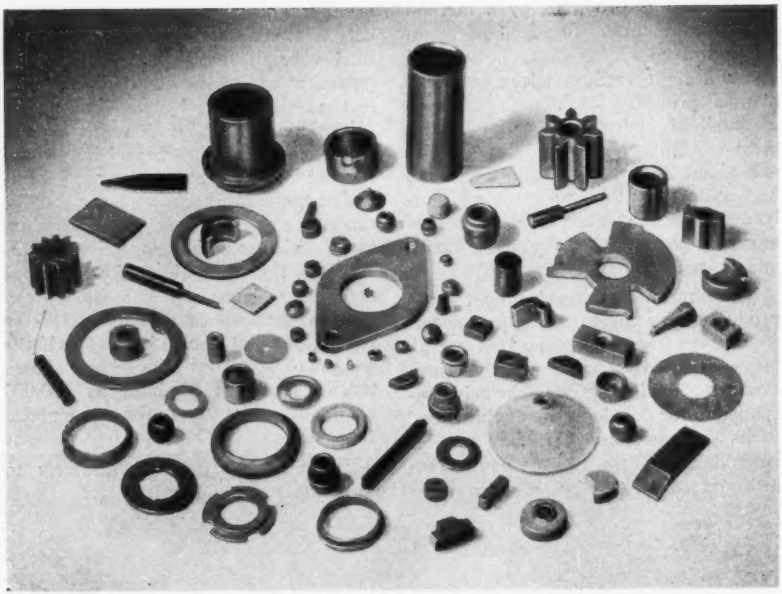
FUTURE OUTLOOK

It is not always wise to predict future developments technical or otherwise. At the risk of being "sawed off" in the future, the author will go out on a limb to predict some future important applications of powder metallurgy.

First, it is safe to say that the general consideration, previously stated for the application of powder metal techniques will remain valid. Present industrial products will be improved, and many new applications for structural parts will be developed because of the cost advantages offered.

The established products such as cutting tools, magnetic materials, bearings, porous metals, friction materials, will benefit by development of improved manufacturing methods with higher quality and lower costs resulting.

The most sensational advances will probably be made in the field of heat resistant materials. The use of refractory metals or their alloys has long been a dream of the gas turbine engineer. Increases in operating temperatures of 200 to 600°F might be possible if these alloys could be used for turbine buckets and nozzle vanes. Unfortunately, the refractory metal (molybdenum) which shows the most promise has very low oxidation resistance at gas turbine temperatures. Its utilization must await the development of coatings, ceramic or metallic, which can provide this protection under conditions encountered in turbine operation. Some doubt exists as to the method of production of molybdenum parts. Vacuum arc melting is currently favored but the production of the powder forms an essential step in the



Typical Powdered Metal Parts Illustrating Diversity of Products.
Courtesy of Kux Machine Co., Chicago, Ill.

fusion technique. The forging of parts from the cast material remains to be solved, whereas parts can be fabricated by pressing the powder to the desired configuration and sintering.

In the production of titanium the powder method has dropped behind in the race for supremacy. The good forging and working characteristics of titanium are responsible for the preferential position the controlled atmosphere arc melting methods now enjoys.

The development and production of ceramics, metal ceramics, and intermetallic compounds seem to offer the greatest possibilities for the application of powder metallurgy. Ceramics offer desirable properties for heat resistant applications since they have good oxidation resistance, a low specific gravity, and a high compressive strength at high temperatures. They are fragile and have poor thermal shock resistance as disadvantages.

The possibilities of metal-ceramic combinations wherein the advantages of metals and ceramics could be combined, with the disadvantages being eliminated or reduced to a minimum has stimulated a major research effort. The development of techniques to bond the constituents and the selection of materials to give the desired properties is a complex technical problem which will require several more years of intensive effort to make significant progress. The dividends resulting from development of methods whereby relatively non-strategic materials with good high temperature properties could be produced for use in gas turbines would be inestimable in a national emergency.

The interstitial or inter-metallic compounds of refractory metal car-

bides, borides, nitrides, is another promising possibility for heat resistant materials. The carbides have high hardness, high melting points and good strength at high temperatures. They lack oxidation resistance, however, and the development of a satisfactory binding material for high temperature service remains to be accomplished. The refractory borides have good high temperature strength and are corrosion resistant but the cementing problem is more difficult than that of the carbides. These technical difficulties are not insurmountable and technical advances will eventually bring many materials into use that are now only laboratory curiosities. The nitrides such as boron nitride offer similar outstanding properties.

The powder metallurgy industry in spite of its long history is still in its infancy. Its potentialities are practically unlimited. It was given a great impetus by World War II, and even with the cancellation of wartime orders, the production of powder has continually risen. The possibilities for economical manufacturing through adoption of powder metallurgy methods are enormous, and it is difficult to visualize anything but a steady expansion of the industry.

In addition to economic advantages, powder metallurgy offers methods of fabrication and production for certain materials and material combinations that cannot be manufactured by any other method. The type and amount of alloying, the grain size, and grain structure of many alloys can be closely controlled to a degree not possible by any other known metallurgical process. The refractory metals with the highest melting points, tungsten, tantalum, and molybdenum, could not be produced without the use of powder metallurgy methods at some point in their processing. Certain alloys can be prepared more advantageously by powder techniques.

As a final prediction, powder metallurgy will play a very important, if not the dominant, role in the development of materials for service in gas turbines, jet engines, and other power plants designed for operation at extremely high temperatures.

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No. 2—(Same view as No. 1) Aerial View of Pearl Harbor Navy Yard—about 1919

No. 1—Pearl Harbor Naval Shipyard about 1947

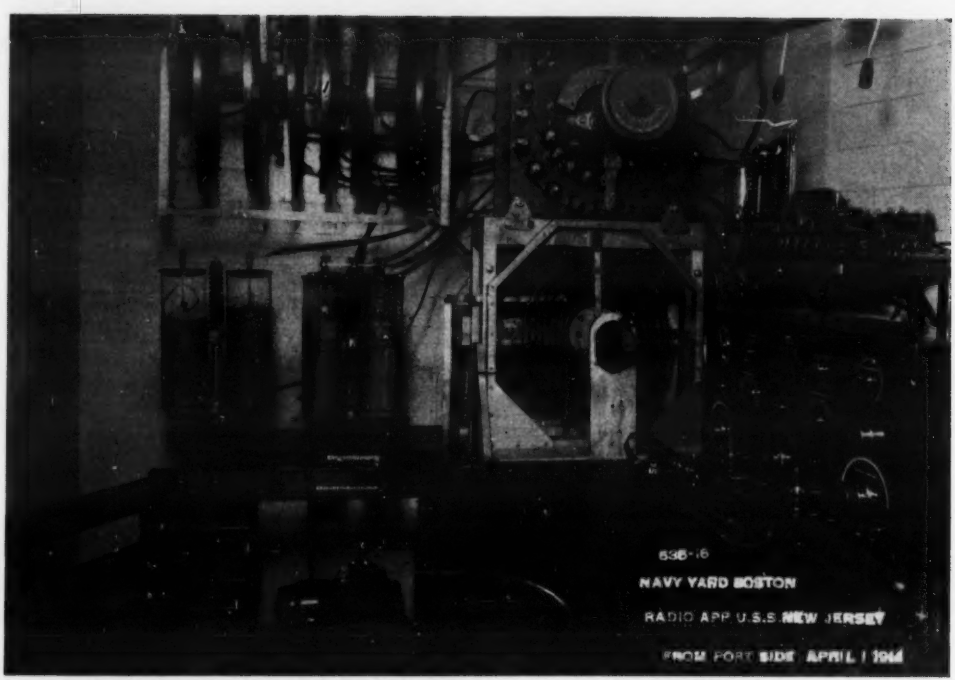

Figure 1.—Typical Early Navy Shipboard Spark Transmitter and Crystal Receiver Installation. U.S.S. *New Jersey*, April 1914. Compare with Figures 2 and 3 (25 years later.)

ELECTRONICS—YOUR FUTURE

A Resume of Historical Interest Concerning a Laboratory Curiosity That has Become the Greatest Technological Force in the World Today

COMDR. CHARLES W. HARRISON, JR., U. S. N.

and

JAMES E. BLOWER, ELECTRONICS ENGINEER

THE AUTHORS

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Comdr. Harrison is presently attached to the Electronics Design and Development Division, Bureau of Ships. He is a member of the Harvard Chapter of Sigma Xi; the American Physical Society; the Institute of Radio Engineers; the Audio Engineering Society; the Harvard Engineering Club; and the American Association for the Advancement of Science.

The opinions and assertions contained in this article entitled "Electronics—Your Future" are the private ones of the writers, and are not to be construed as official or reflecting the views of the Navy Department or the naval service at large.

JAMES E. BLOWER, Electronics Engineer, attended Ohio University, Athens, Ohio and Ohio State University, Columbus, Ohio where, in 1934, he received the degree Bachelor of Science.

He was a radio experimenter and amateur and became active in the United States Naval Communications Volunteer Reserve in 1928. In the early 1930's he entered the field of radio broadcasting and was associated with several prominent broadcasting stations in various engineering and managerial capacities. In the late 1930's he was engaged in high frequency electronics development work including frequency modulation and facsimile applications. During this period he was a frequent visiting lecturer on commercial electronics applications at universities and civic organizations.

In 1943, Mr. Blower, then a Lieutenant (junior grade), U. S. Naval Reserve, was assigned active duty at Princeton University. Later, he was transferred to the Staff, Commander Service Force, U. S. Pacific Fleet as Assistant Radar Officer. During this tour of duty, he was promoted to Lieutenant and was awarded a Navy commendation for the excellence of the performance of his electronics duties. In 1945 he was ordered to report to the Chief of the Bureau of Ships and was assigned as Assistant to the Officer-in-Charge, IFF and Radar Beacon Design Section. At his request in the rank of Lieutenant Commander he was released to inactive duty late in 1946. He is now an electronics engineer in the Navy Department, Bureau of Ships and serves in the capacity of Special Assistant to the Director, Electronics Design and Development Division.

Mr. Blower holds the degree Bachelor of Law from Georgetown University and is a member of the Bar of the United States District Court for the District of Columbia and the Bar of the United States Court of Appeals for the District of Columbia as well as the Bar of the Federal Communications Commission.

He is a member of the Ohio State Chapter of Tau Kappa Epsilon and the Georgetown Chapter of Phi Delta Phi.

INTRODUCTION

Since the days of the Navy's first wireless transmission and reception very early in the 20th century the art has grown into one of the greatest achievements of the scientific and engineering world — Electronics. The story of electronics as it relates to the development of the modern Navy, which includes the Naval Air Arm, the Surface Force, the Submarine Force and the Marine Corps, is one of the most interesting stories in the history of mankind. The historian in this field of science is shocked by the fact that the best minds of our times both military and civilian were unable to foresee the extent of the impact of the introduction of electronics on modern society. Throughout our sights have been too low.

This historical review is limited to the accomplishments of the Navy, principally the Bureau of Ships. Concurrently, of course, during the later years of the period covered both the Signal Corps of the Army and, since 1944, the Air Corps have been engaged in similar work. Where applicable, the work of the three services has been well coordinated.

In its earliest application, wireless was considered an effective means of bringing the "Message to Garcia" at the speed of 186,000 miles per second. Today, electronics has been harnessed to gear our way of life to a world in which things happen almost instantaneously. In this critical moment of history, the future welfare of every citizen of the United States is bound up with the progress and advancement of the Navy's electronics program. This is the era in which "early warning" delivered by electronics devices may mean National survival. In this world where trouble spots develop quickly, appropriate defensive measures must be taken in a matter of hours, minutes or even seconds. In the present "cold war" our national prob-

lems are substantially dissimilar to those faced by this country on 7 December 1941 for the reason that other nations have not been unaware of the indispensability of advanced electronics techniques.

In time of future emergency we shall have no period of days, months, or years to muster our forces. Rather—defensive action—if it is to be effective—must come many thousandfold faster than heretofore, otherwise those of us who survive may whisper in bondage of the war that might have been.

The nation's research and development program must lead to the development of electronics equipment necessary to provide the quick acting nerve centers which are the only means of warning our citizenry, marshaling our country's strength, coordinating and directing our Naval global strategy and defending our cities, villages, homes, farms and factories from the fiery sword of a would-be aggressor. In the crucial days of any future war, undertaking operational missions without adequate guiding electronic "nerve centers" will be like flying through zero-zero weather without instruments; it will be blind maneuvering, not flying, and ultimately the only direction one can maneuver blindly in a fog—is down.

One thought we must have in mind at all times—Electronics is finding applications never considered within the realm of possibility. Let us not be so naive as to belittle the intelligence of any potential enemy by concluding complacently that we lead the field. Other nations are making advancements. Our best defense is to maintain an aggressive lead. Electronics is the only known feasible means of control for delivering modern, long range defensive weapons in time, in quantity, and in appropriate geographical locations to assure continuance of our way of life.

The United States Navy rightfully takes great pride in one of the glittering pages of its history of scientific achievement—the dominant role it has played in the development of the electronics science to its present advanced state. Electronics plays a vitally important part in the daily life of every citizen of the United States because of this pioneering effort of the Navy. Our people, whether at home, at work or at play live in a welter of electronics: radio and television broadcast receivers, police radio systems, radio and electronic systems in common carriers (airplanes, railroads, taxis, buses, ships), private automobile radios, medical applications of electronics (diathermy, X-ray, radio knife, superstethoscope, fluoroscope, electroencephalograph (brain wave recorder and cardiograph), movies (sound on film), timing of races, "talking books" for the blind, hearing aids, facsimile, color matches, burglar alarms and radar cookers to name only a few. In the future, every citizen will enjoy the comforts, entertainment and protection of more and more additional electronic servants which will be regarded by him as necessities of life. Electronics is a service. Its capacity to serve the American public is bounded to-day only by the limitations of the imagination of electronics engineers and scientists. Because the Navy is the greatest engineering organization in the history of the world—the Navy should hold the key to the future of electronics. The midget radio that brings the morning newcast into ones home, and the electronics navigational aids aboard a stratocruiser winging its way over the Rocky Mountains are each closely linked with the Navy's achievements in electronics.

Electronics is not the abstruse "black magic" that some people would regard it, engaged solely in accomplishing complicated technical tasks, but a social servant intimately coupled with human history and destiny. It is

to be emphasized and re-emphasized that the Navy electronics research and development program though directed toward solving military problems offers as an inescapable by-product constructive electronics devices that are in daily use by the civilian population of our country. The Navy electronics program is not to be confused with military electronics applications alone. The term is necessarily far more inclusive.

The Navy early realized the strategic importance of radio communication for ship to shore and ship to ship use. In 1903 the Navy had in use spark and arc transmitting equipment together with suitable receiving sets. At the out break of World War I, the Navy had gained considerable experience in the technique of radio communication. In order to harness this science most effectively it was realized that a comprehensive program of research and development was necessary. The Congress appropriated funds for this purpose. Planning, programming and control of this program became the order of the day. At the advent of World War II the early concept of the potentialities of radio had become obsolete. Electronics had become such an expansive science that scientist and engineers especially skilled in its ramifications were among the most critically required classes of personnel so necessary to effectively prosecute the war. Some of the most hopeful pages of history record the accomplishments of the citizen Navy which rapidly and efficiently was molded into the regular Naval Service. The accomplishments of this war time era stand as a tribute to American ingenuity.

The design parameters for radio communication equipment were directly applicable to the development of radar, loran and similar electronics system to be discussed later. Scientists and engineers are agreed that the frame-work was well-laid by the Navy prior to World War II and permitted the tremendous expansion in the electronics field required by the advent of war. During these years of conflict when time was the essence of our country's salvation the Nation's ability to expand the electronics industry to some 800% of its prewar production level was one of the major contributing factors to victory.

The demands placed upon Electronics by the Armed Forces were so great that at the close of World War II, no one person could comprehend all the advances made in this new science. Peace has brought a new era to Electronics. Now it is contributing to the reconstruction of the world and is fast becoming an even greater convenience and beneficience to civilization. The responsibilities placed by the nation upon its Navy require that the navy maintain constant vigilance with respect to the ever present possibility of war. The future of electronics and its influence on our national security as well as on our standard of living in peace is of great concern to the Navy.

One aspect of electronics is its ability to extend mans' visual and auditory senses beyond those normally provided by the functions of the human body. For example, radio enables a person to hear (almost instantaneously) a program originated thousands of miles away. Television permits a person to see a program at distances far beyond those at which they could be distinguished by the unaided eye. Radar (or Sonar) enables a person to detect an object at a relatively great distance and establish its coordinates with respect to a known point. This vision is sensibly unimpaired by darkness, fog, clouds, rain and smoke which detrimentally affect direct vision. A second aspect of electronics covers control devices. These are extremely important because they permit the control of heavy plant machinery, for example, with accuracies, speeds and economics heretofore unknown. This phase also includes control of pilotless aircraft and missiles. A third aspect of

electronics embodies telemetering—an electronics method of relaying data from an operating point to a more convenient control or recording point, such as transmission of data from a missile in flight to its control or recording station; aerological, meteorological and weather observation balloons and drones for measuring intensities of radiation resulting from atomic bomb explosions. A fourth aspect of electronics embodies that vast and growing field of medical applications promising much in the improved health, general welfare, and comfort of our population. A fifth aspect of electronics worthy of special mention is its applications in mathematical computing devices. It is with electronic computers that the most significant advances in engineering principles and techniques have been made. One is not to infer that with the advent of electronic computers the physicist or engineer may dispense with his thinking, but rather that the computer takes the tedium out of involved numerical processes that heretofore required the joint efforts of mathematicians and hand computing machine operators days, weeks or even months to carry out. An electronics computer is not and never will be a device to circumvent muddleheadedness. It is capable of providing intelligent answers only to intelligent questions. The greatest field of usefulness for electronics computers is in the numerical analysis of problems where the fundamental principles are well established, but where their application to basic problems is beset with severe mathematical difficulties. Even the economist has found the electronic computer indispensable to the study of modern business problems within his field! Electrons stands on the threshold of revolutionizing modern business management practices. It is cutting the "Gordian Knot" in such fields as accounting, stock control and cataloging.

RADIO COMMUNICATIONS

The Navy made early operational use of radio as a medium of communication. Naval strategists foresaw the possibility of radio as an effective means of deploying the fleet to greater advantage. The ability of fleet commanders to maintain constant communication with our bases as well as with other operating forces was tantamount to increasing tremendously the number of ships at sea. This is true because for the first time it became possible to alter operational plans on short notice. The introduction of radio communication to the fleet stands as one of the great advancements in the science of naval warfare.

When the United States entered World War I in 1917, the Navy had acquired many years of experience in radio communications. The state of the art in that day is a matter of historical interest. During World War I (as in World War II), the Navy scoured the country to obtain the services of scientists, engineers and technicians skilled in radio science. During those war years, young men were trained in this new art. Of the 6,000 radio amateurs then active in this country, some 4,000 entered one of the military services. The termination of hostilities released to civilian life several thousand skilled men who became the nucleus of the rapidly growing radio industry. Radio broadcasting became a reality almost over night. History has repeated itself once more after World War II. Service trained electronics engineers and technicians returning to civilian life are the corner stone of today's rapid advancements in civilian electronics. The Navy prides itself in teaching every one of its men a skill. Electronics is one of the best examples of the benefits derived by the general public as the result of this Navy policy.

The history of the growth of elec-

tronics in the Navy follows two paths. First, the design and development of new and better electronics equipment for established services as well as the design and development of electronics equipment for new applications. Second, improvements designed to increase the pay load of existing radio communication facilities. The latter is necessary because of the fact that the radio frequency spectrum, when viewed as a prime natural resource is susceptible to limited exploitation only. Every new transmitter placed in operation requires an operating frequency or band of frequencies. Because there is a limitation on the number of frequency channels, one means of solving this ever present problem is to use one transmitter for more than one purpose.

During the past quarter century, Navy radio transmitters have been designed to operate from 15 kilocycles per second into the super high frequency range having an upper limit above 30,000 megacycles per second. Technical developments have been achieved to insure that a radio transmitter maintains close adherence to its assigned frequency. Improved methods have been devised for the modulation of the radio carrier by voice and other forms of intelligence. Mechanical design of radio equipment has been improved so as to enable it to witstand the rigors of service when installed aboard combatant vessels. The power output of radio transmitters has been progressively increased many fold. Techniques and procedures have been devised to increase the speed of processing the transmission of radio intelligence. The operation of Navy radio transmitters has been greatly simplified.

In the early years of radio communication, frequencies above 1500 kilocycles per second were considered to be of no practical value. For this reason commercial radio interests considered this portion of the spectrum to be of little economic interest until relatively late in the development of the art. In tracing the history of experimentation in high frequency communication, the work of the radio amateur must be given great credit. The Navy vigorously pursued a development program designed to utilize frequencies above 1500 kilocycles per second. As early as 1919, the Navy had developed a series of radio transmitters designed for shipboard use capable of operating on frequencies as high as 2,000 kilocycles per second. By 1925 the frequency range of Navy shipboard transmitters had been extended to 3,000 kilocycles per second.

About 15 years ago, the Dow electron coupled oscillator was developed. One great advantage of this type of oscillator is that its frequency stability is not appreciably affected by temperature change. Another important feature is that it is capable of operating at any frequency within a given band of frequencies (by appropriate adjustment). This fact is in contrast to crystal oscillators where the oscillator develops a discreet frequency depending upon the characteristics of the crystal employed.

In 1935, the Navy developed a 30 to 60 megacycles per second transmitter and receiver for voice and telegraph service. Equipment designed for operation in the 60 to 80 megacycles per second range followed in 1938. This equipment served as one of the outstanding inter-ship communications systems during World War II. It was particularly important for communication between ships serving on convoy duty. In 1943 radio transmitters were developed by the Navy to operate in the 115 to 156 megacycle per second band. This was followed in 1944 by the development of equipment for use in the 225 to 400 megacycles per second band.

During the period of advance into the high radio frequency spectrum, the Navy had an increasing need for high powered low frequency transmitters.

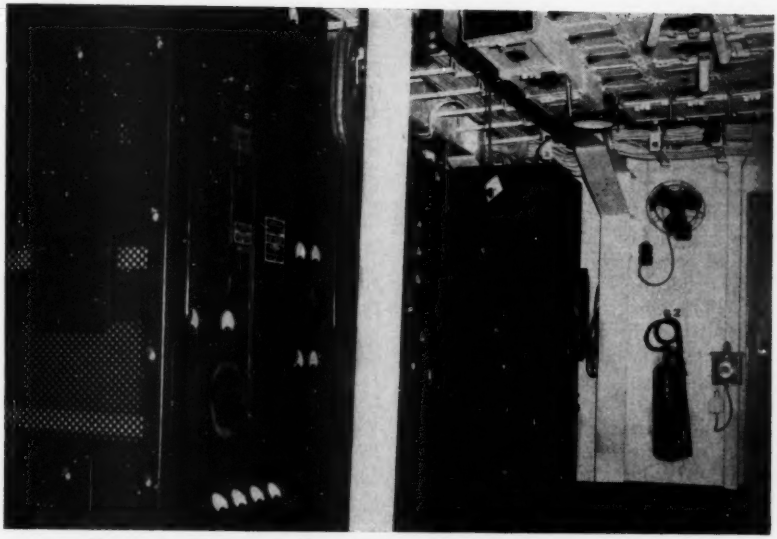


Figure 2.—Modern Radio Transmitter Installation Aboard Ship.

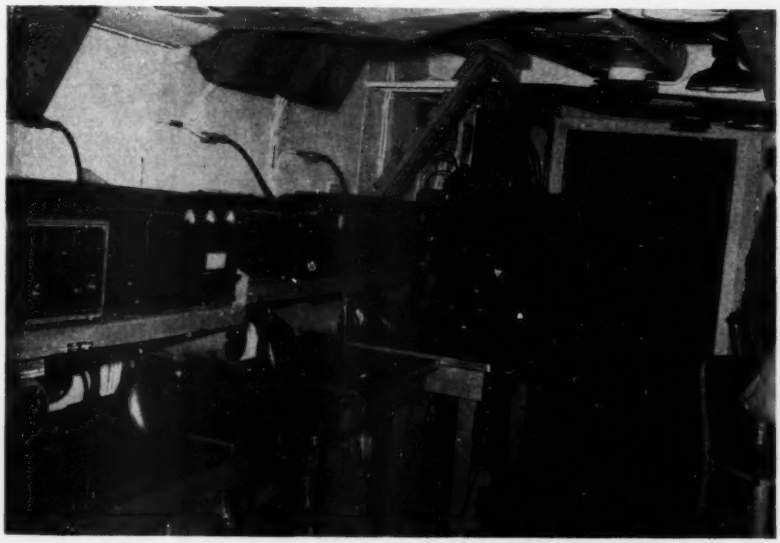


Figure 3.—Modern Radio Receiver Installation Aboard Ship.

These were required to provide reliable ground wave coverage of fleet broadcasts. In general radio waves in this frequency region are not susceptible to skip distance phenomenon. Thus, developments were concurrently prosecuted in the lower end of the frequency spectrum as well as in the higher regions. By 1934 a low frequency transmitter had been developed by the Navy capable of delivering 500 kilowatts of power into its antenna system. As a result of the basic techniques evolved by constructing this low frequency transmitter, the Navy is now increasing transmitter power output to insure reaching ships at sea regardless of their locality of operations.

The Navy originally developed radio transmitters in 1939 providing rapid selection (from a remote point) of preset channels. The basic principle of remote channel selection has since been applied to various Navy transmitters including the present 225 to 400 megacycles per second sets. Current developments are directed toward the design of oscillators for transmitters having stabilities comparable to those afforded by the use of crystal control. The great advantage of such transmitters is that they are capable of continuous frequency coverage without requiring a separate crystal for each channel. Continuous frequency coverage by a transmitter is considered to be of importance as a precautionary measure against enemy jamming. Preset and manually tuned transmitters may be replaced at a later date by equipments in which frequency is remotely selected by automatic means. Navy technical specifications covering present transmitter developments incorporate features of this character.

Early Navy radio receiver research and development was accomplished at the Radio Test Shop, Washington Navy Yard. Personnel attached to this Shop were later transferred, and became the nucleus of the Radio Division of the Naval Research Laboratory. The radio industry, during its infancy, lacked the capital, the technical personnel, and the laboratory facilities to engage in little more than the fabrication of production equipment for the Navy. This equipment was built to conform to drawings, specifications and working models provided by the Radio Division of the Naval Research Laboratory.

It is of interest to note that prior to 1930 progress in the development of communication receivers lagged behind that of radio transmitters. This condition was not due to a lack of motivation or invention in this field but rather to economic factors which were not conducive to rapid progress in military radio receiver design. The period just preceding 1930 saw the radio industry concentrating its activities on entertainment radio receivers. The market necessary to sustain rapid progress in military receiver development did not exist. Industry cannot afford the luxury of developing new and better equipment unless there is a market available to absorb its product profitably. Research and development is a costly undertaking. The lack of research and development means stagnation. National security can be achieved only through the development of new and better equipment for military purposes. An essential by-product of developments of this character is an increase in the know-how which may be applied to the production of better equipment for civilian use.

The first important series of radio receivers designed for shipboard use was developed under Navy contract by the Westinghouse Electric and Manufacturing Company in 1929. This work continued until 1933. Of historical interest is the fact that the last models of this series of receiving equipments were installed aboard the Navy dirigible U.S.S. *Macon*, which was so tragically lost off Point Sur, California. One of the major technical advancements represented by this series of

equipments was that for the first time shipboard communication receivers employed gang-tuned radio frequency amplifiers. They covered the frequency range of 15 to 22,000 kilocycles per second.

In 1934, the first completely alternating current powered shipboard superheterodyne communication receiver development was undertaken by the Navy. Prior to this date, shipboard radio receivers were battery powered. Because of their size and weight, these superheterodyne receivers did not lend themselves to extensive installation aboard small ships such as destroyers and submarines. Further radio communication receiver developments were undertaken to alleviate this problem. As a result, a new series of tuned radio frequency receivers employing autodyne detectors for continuous wave code reception were developed. These receivers covered the frequency range of 15 to 16,000 kilocycles per second and 300 to 23,000 kilocycles per second. They were completely alternating current powered. From a technical point of view, these receivers may be regarded as the "second generation" of the original models developed at the Radio Shop of the Washington Navy Yard. From the standpoint of simplicity of operation, maintenance, and excellence of overall performance, these receivers have no peers even today. In the early part of 1940, development was started on a series of three Navy standard communication receivers designed for ship and shore use. The outbreak of hostilities between the United States and Japan occurred prior to the completion of this project. At that moment, the Navy was confronted with a huge demand for electronics equipment of this type. The general public as well as radio amateurs were asked to sell their communication receivers to the Navy. The response was most gratifying. The problem was to get radio communication equipment installed and operating aboard ships in the least possible time. One of the interesting steps taken was to reclaim antique models of Navy radio receivers. These were modified to permit the use of modern electron tubes and to operate on alternating current. Some of them were installed on the fifty over-age destroyers delivered to Great Britain in connection with the acquisition of Naval bases in the Western Hemisphere. This act indicates how desperately the Navy needed communication receiving equipment at that time. Under other conditions, these antique receivers would never have been considered for further use. But the fate of the nation hung in the balance. Drastic action was essential. The Navy met the challenge!

New electronics development projects were inaugurated at once to meet the urgent needs of war. Among the more important of these must be mentioned the panoramic methods of signal presentation. The panoramic receiver is an electronic device capable of visually displaying the presence of signals within a selected segment of the radio frequency spectrum. It is a most useful search and intercept device. Attention was given to the development of antenna multi-couplers. This device permits many receivers to operate from a single antenna. It must be remembered that space limitations aboard ship preclude the rigging of many antennas.

The importance of entertainment receiving equipments as a means of maintaining high morale among the fighting men of the Navy was given full attention. The Navy developed a special receiver for entertainment purposes that could be operated aboard naval vessels in combat areas without danger of detection. This was accomplished by effective shielding and other means. The average entertainment receiver incorporates a radio frequency oscillator; therefore it may behave like a miniature transmitter. Its signal can be easily detected by electronic means. Accordingly, it will compromise the

presence of a ship as certainly as though the ship were fully lighted! A ship equipped with improperly designed receiving sets is an easy prey for lurking submarines.

To meet the demand for communication channels and to maintain fleet security, high priority electronic developments were undertaken by the Navy in the ultra high frequency range. These frequencies offer a measure of communication security because radio waves at these frequencies tend to be limited to line of sight distances.

Post World War II radio receivers under Navy development are being designed for light weight, compact construction. Ruggedized subassemblies and miniaturized components are used in these receivers. Ruggedization, miniaturization and standardization are important fields for future radio receiver developments.

Radio photo equipment and facsimile equipment represent another important phase of the Navy's broad communication systems program. The need existed for the ability to transmit rapidly weather maps, photographs, drawings, and other high priority graphic data. This service was required for the numerous mobile units of the fleet and overseas bases. For many years naval strategists dreamed of the possibility of transmitting intelligence of this character. It remained for electronics to provide the means. During the early years of World War II, technological advances progressed to a point where daily use of this type of facility could be relied upon. In 1944, the Navy procured sufficient facsimile equipment for installation at Pearl Harbor, Guam, San Francisco and certain ships of the Pacific Fleet. At the close of World War II, daily operating schedules were maintained between facsimile stations separated 4,000 to 6,000 nautical miles. The rapid delivery of pictures of the Japanese surrender ceremony aboard the U.S.S. *Missouri* in Tokyo Bay, were transmitted by a facsimile transmitter aboard the U.S.S. *Iowa* in Tokyo Bay to San Francisco, California, a distance of approximately 4500 nautical miles. An equivalent system was used to transmit the first Bikini atom bomb test pictures from the U.S.S. *Mt. McKinley* at sea, off Bikini Atoll—a distance of approximately 4100 nautical miles. These photographs were made available to the press within a few hours after the explosion of the bomb. This feat alone surpasses the fondest dreams of Jules Verne! Equally outstanding accomplishments culminated in the record breaking scheduled transmissions between the U.S.S. *Burton Island* in the Antarctic and Washington, D. C. a distance of approximately 9,200 nautical miles—another manifestation that electronics is effectively shrinking the concept of global distance. For a period of several weeks, daily weather maps were exchanged between the U.S.S. *Burton Island* and Washington. A great contribution to long range planning and weather forecasting has been made.

During the years following World War II, facsimile has been accepted as the most economical means of rapidly disseminating plotted and analyzed weather maps. A joint Air Force-Navy-Weather Bureau facsimile network now connects the major military and civilian airports of this country. This technique has brought about considerable savings in time and money necessary to prepare weather instructions so vital to air traffic control and air safety.

The Navy has prosecuted a vigorous program of basic and applied research and development in the facsimile field. These projects are being undertaken both in Navy laboratories and commercial laboratories. In no electronics application has the public more to gain than in future developments in this field. Tomorrow's printing press may well be an electronics device!

Prior to 1932, the Naval communications system employed manually oper-

ated Morse telegraph circuits for both radio and land line communication. Highly skilled operators were employed. They were capable of handling traffic at speeds of 40 to 50 words per minute. In 1932, diversity reception was first employed by the Navy. With this innovation, fixed point to point radio telegraph circuits were rapidly converted to automatic operation. Machine transmission originating from perforated tape as well as reception on tape recording has replaced the old time operator in many instances. Speeds were increased from 50 to more than 300 words per minute. This advance effected further economics in the operation of the Navy's communication system through the utilization of heavier pay loads. Fewer transmitters are required to perform more work.

Domestic communication by means of teletype began in the Navy in 1939. At its inception, this service used leased lines and leased equipment. By 1944, Navy owned and operated equipment had been installed. Semi-automatic message switching equipment permitted relaying and rerouting of messages without retyping.

Although the use of radio teletype had been attempted experimentally as early as 1930, it was not until the development of the system of frequency shift keying together with suitable terminal equipment that radio teletype became sufficiently reliable for naval use. In 1944, the first long distance point to point radio teletype service was inaugurated. Within a short time thereafter, the entire Navy radio communication system began its conversion from automatic Morse operation to radio teletype operation. Today, the Navy's teletype communication system spans the world.

The pressing demand for the efficient handling of greater and greater volumes of traffic lead to the development of improved systems for handling two or more transmissions simultaneously over the same transmitter. This system is called multiplexing. In August 1944, the first mechanical time division multiplex system was placed in service. It provided four simultaneous teletype channels for transmission by one radio transmitter. By August 1945, twelve of these systems were in regular use. It is self evident that tremendous economies are realized as the result of this advance.

To further satisfy the need for more and more communication systems, a frequency multiplex system (single side band system) was developed to provide a maximum of six teletype channels and one voice circuit. This system uses only one transmitter and one receiver. The first of these systems was put in service in January 1946. Seven are operating successfully at the present time.

Developments in the field of television prior to World War II opened the possibility of transmitting moving pictorial information. During World War II the Navy developed complete television systems for airborne reconnaissance and other military purposes. Many of the results of this research and development pioneered present advanced television techniques and standards which are being used commercially. These have contributed greatly to the advent of television in the American home.

Since the close of World War II, the Navy has undertaken further electronics research and development projects in the field of high definition television as well as in color television. These projects are virtually certain to become part of civilian television in the future.

Radio is one of the oldest of the electronics arts. It did not have, for example, the benefit of the glamour and secrecy that surrounded wartime radar development. Nevertheless, radio has moved to the fore with its full share of important advances. Radio is one of the tried and true "bread and butter" items of the Navy. The Red Cross and

other emergency services owe a large part of their effective and expeditious mobilization to relieve suffering to being advised of the needs by radio (which is often the only remaining link between the disaster location and the outside world). Radio not only provides the essential communication service in time of floods, hurricanes and other disasters, but is indispensable to our Forestry Service for locating and controlling forest fires. Thus radio is a factor in conserving our natural resources.

Let us never forget one very important point—in the hour of national emergency, it is radio that must spread the alarm to every ship, station and hamlet!

RADIO DIRECTION FINDERS

In 1912 the Navy Department began to experiment with various proposals for obtaining directions of arrival of radio signals. Radio direction finding equipment was considered to be of great value for locating enemy ships and for navigational use.

Early radio direction finders utilized manually rotated loop antennas for signal pickup. Instruments of this type are susceptible to errors of varying magnitude, depending on the polarization of the incoming signal. Radio signals in the low and medium frequency bands are usually vertically polarized with respect to the earth's surface, and under these circumstances the loop antenna direction finder is capable of giving reasonably accurate bearing indications. This presupposes that the signal does not depart significantly from the great circle path between the transmitting and receiving points. Any obstructions in the vicinity of a non-shielded loop antenna, such as ship superstructure, will result in erroneous measurements. Accordingly the very early direction finders were not well adapted to ship-board use.

By 1916 an improved low and medium frequency direction finder had been developed by the Navy in collaboration with the National Bureau of Standards, and twenty of these were installed in the Fleet. During the period of United States participation in World War I an elaborate shore radio compass system was completed, and many vessels were fitted with radio compasses for detecting the presence of and obtaining fixes on enemy vessels. By 1924 over 5,000 bearings a month were furnished merchant ships alone from the forty eight stations on the Atlantic and Pacific Ocean coasts. There was no charge for this service.

During the interval between World War I and World War II great efforts were made by the Navy to reduce error indications caused by the polarization of the incoming radio wave. This was necessary because increasing emphasis was being placed on the use of higher and higher frequencies for communication purposes. At high frequencies, radio waves from distant stations are ordinarily of random polarization. Under these circumstances single loop antenna direction finders are subject to severe errors in bearing indication. It was found that polarization erraticacies may be reduced by the use of two suitably oriented dipole antennas in lieu of a single loop antenna. The Adcock direction finder employes two vertical antennas for signal pickup attached at either end of a horizontal crossmember. The latter is manually rotatable in the azimuth plane. By 1936 equipment of this type was in service, but because of the nature of the design and certain technological reasons the equipment was suitable for shore station use only. High frequency direction finding networks were soon established ashore, and the ability of these direction finders to take accurate bearings

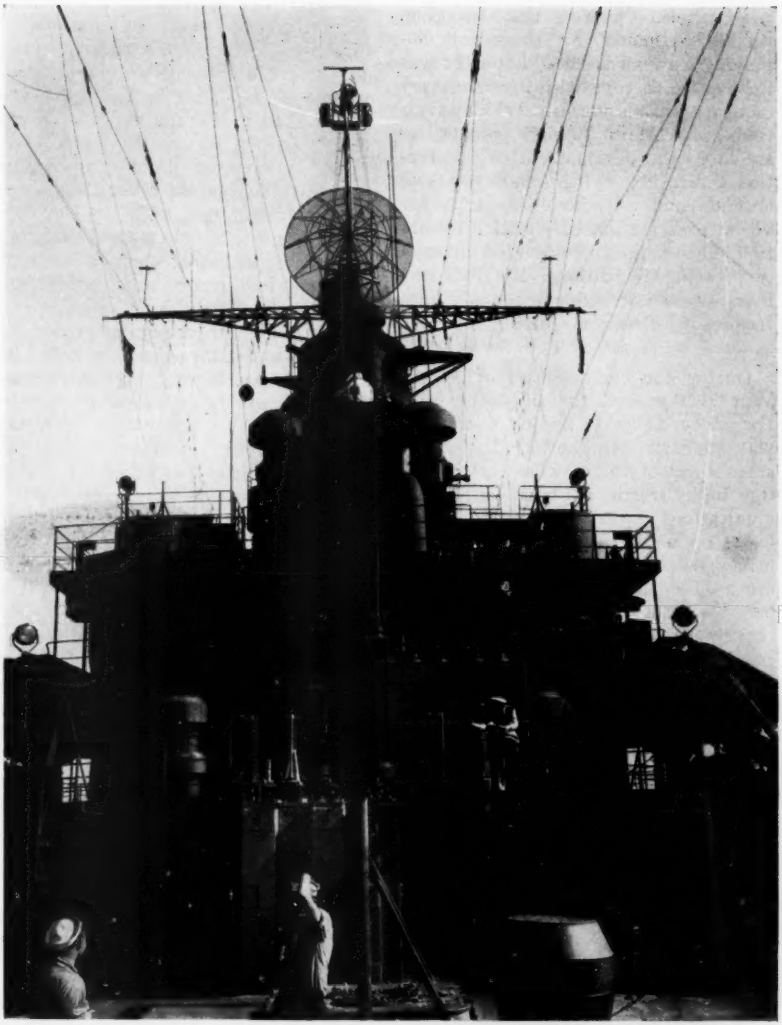


Figure 4.—Antenna Installations Aboard a Command Communications Vessel.

on distant stations provided service in the field of sea rescue as well as ship location and navigation.

Experience proved that direction finding equipment for shore use employing manually rotated antennas was inadequate to cope with brief military tactical transmission. In 1940 investigations of certain French patents resulted in the development of a direction finder employing a non-rotatable antenna and a cathode ray tube for visual presentation of signal information. This equipment provided automatic bearing indications. By 1942 the Navy was constructing automatic high frequency direction finding stations ashore.

During the early phases of World War II the need for shipborne high frequency direction finding equipment was emphasized by the fact that enemy submarines (which were employing the high frequency band for communications) were inflicting serious losses on vital shipping. Early experiments with high frequency direction finders installed aboard ship revealed that site conditions are critical in relation to the proper performance of the equipment. Any obstructions in the vicinity of the antenna, such as masts or other superstructure causes reflections and reradiations resulting in erroneous bearings being indicated. Using information obtained from British shipboard experiments and the data previously acquired through its own work, the Navy developed a new direction finder which performed successfully aboard ship. Although the new equipment did not overcome the necessity for proper site selection it was learned that errors of indication could be reduced by taking certain precautions and devising calibration techniques. This work permitted the extraction of more dependable information from the equipment. Installations of direction finders made during 1943, 1944, and 1945 on destroyers and escort vessels of the Atlantic Fleet played a major role in eliminating the U-boat menace.

The function of direction finding as an aid to navigation aboard ship was made a minor one with the development of such new systems as Loran, but new fields, including countermeasures, intercept, intelligence, and rescue, were providing new uses for the equipment. Enemy radar transmissions could be detected and their direction noted at distances considerably greater than the maximum range of radar contact. In 1944 the development of direction finders covering frequencies up to 5,000 megacycles per second for ship and aircraft use were nearing completion and by the end of that year these equipments were installed.

The increasing numbers of aircraft employing very high frequencies for communication has opened a new field of use for the high frequency direction finder. The Navy has designed and produced direction finders for use in conjunction with blind landing systems for guiding and homing aircraft.

Direction finders have an important application in Meteorology—in tracking free balloons, and determining the direction of electrical storms which often accompany weather disturbances.

Presently commercial airliners as well as military aircraft employ automatic direction finders as a navigational aid. These electronics devices add greatly to safety in the air.

RADAR

Radar is simply an abbreviation for the words "*RA*dio *D*etection *A*nd *R*anging." Fundamentally, radar enables one to detect by electronic means the existence of an object and determine how far it is away and in which direction. Radar functioning depends on the precision measurement of the small time interval (in millionths of a second) between the instant the radar

Figure 5.—Antenna Installation For Early Navy Radar System (Naval Research Laboratory—1938).

set sends out a radio wave of short time duration until the time the radio echo from the target is received Knowledge of this time interval enables one to predict accurately the distance to the object because radio waves travel at sensibly constant speed, namely 186,000 miles per second. The bearing of the target is ascertained by making use of the directional characteristics of the radar antenna. The same antenna is used for both transmission and reception.

Radar sets of appropriate design are capable of providing information relating to target height.

A chronological survey of U. S. Naval Radar breaks down sensibly into five periods, namely; Research Period, (1922-1939); Introductory Period, (1940-1942); Improvement Period, (1943-1944); Replacement Period, (1945-1946); Postwar Development Period, (1947-).

The Research Period (1922-1939) was characterized by difficulties in experimentation at radio frequencies where radar effects become important. The experimenters were beset with problems of obtaining special vacuum tubes and other electrical components operable at high frequencies. Allocation of funds for such research could not always be provided in adequate amounts. Even personnel were not fully conditioned to the bizarre behavior of high frequency radio waves. Experimental radar models required considerable attention during operational trials.

The development of Radar during the Introductory Period (1940-1942) was dictated almost completely by urgent operational needs. The forces afloat became acquainted with radar, discovered most of its potential uses, and demanded quantities of equipment far in excess of the supply. Radar grew from the status of a secret weapon to the leading weapon of the war. New applications were born during this period such as Ground Control Approach (GCA) for the safe landing of aircraft, Long Range Navigation (LORAN), and Navigational Radar Beacons. The extremely important elec-

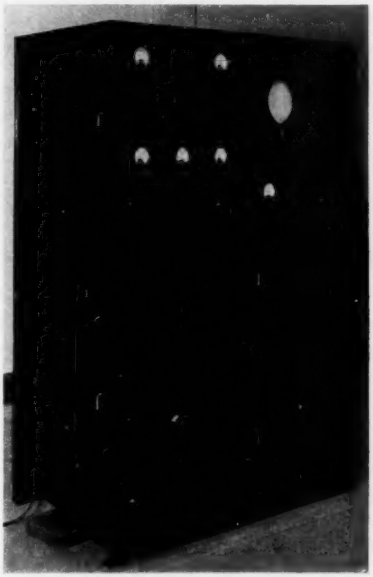


Figure 6.—Early Navy Radar Equipment (Developed by the Naval Research Laboratory—1938).

Figure 7.—Operator's Console of Navy Air Search Radar.

tronic equipment for identification of friend from foe was introduced during this period.

Radar grew of age during the Improvement Period (1943-1944). The forces afloat had learned how to use the radar equipment at hand and demanded improved equipment tailored for the operational job. Installation rates of equipment assumed staggering figures. Maintenance became more systematized and schools were turning out large numbers of well trained radar personnel.

The Replacement Period (1945-1946) was brought on by such factors as, wearing out of early radar equipments, need to reduce the number of types by standardization, and the need for more and better radars. The war-time life expectancy of radar equipment was as short as three years.

The Post War Period (1947-) initially brought about consolidation of radar techniques and greatly increased applications in civil agencies. The formation of the Research and Development Board stimulated the dissemination and exchange of technical information between the services. The struggle for improvement in the performance of radar continues although the possible margins of improvement are decreasing.

Naval Radar had its beginning in September 1922 from experiments conducted by A. Hoyt Taylor and Leo C. Young, of the Naval Research Laboratory, who observed a distortion of radio signals caused by their reflection from ships on the Potomac River as they steamed by the Laboratory. They suggested that this phenomenon could be used to detect enemy vessels in darkness, bad weather, or smoke. Experiments in June 1930 by the Naval Research Laboratory, showed that radio signals reflected from an airplane

Figure 8.—Submarine Radar Antennas.

could be detected, thus revealing the presence of the airplane. On receipt of this information the Bureau of Engineering (now Bureau of Ships) issued a request January 1931 to "Investigate the use of radio to detect the presence of enemy vessels and aircraft". By June 1932 the Naval Research Laboratory had developed an experimental continuous wave radio detection system capable of detecting under certain circumstances, an airplane at a distance of 50 miles. During this year (1932) all Navy information on radio detection was turned over to the Army, and the Army Signal Corps began research and development on radio detection. By 1934 the Navy had experimented with pulse type radio detection, and because of considerable progress in the radio manufacturing industry, availability of component parts permitted the development in 1936 of an 80 megacycle per second pulse type radar having a range of 45 miles on aircraft.

The following year a 200 megacycle

per second radar was developed and installed on a five inch gun mount of the Destroyer *Leary* and tested at sea. Improvements by 1938 permitted bearings and ranges to be obtained on aircraft 100 miles distant.

The year 1939 marked the beginning of the transition of radar from the purely basic research stage to commercial development and production. Operational tests in 1939 of the latest Naval Laboratory Radar on the U.S.S. *New York* were so successful that six production models were installed on the U.S.S. *California,* U.S.S. *Yorktown,* U.S.S. *Northampton,* U.S.S. *Pensacola,* U.S.S. *Chester,* and U.S.S. *Chicago.* These installations were of great military significance to forces afloat and awakened them to the tremendous possibilities of radar as a new Naval weapon. High flying aircraft could be detected and located to a distance of some fifty miles. Fourteen more of these equipments with improvements were obtained in 1941 and were installed on the U.S.S. *Texas,* U.S.S. *Pennsylvania,* U.S.S. *West Virginia,* U.S.S. *North Carolina,* U.S.S. *Washington,* U.S.S. *Augusta,* U.S.S. *Lexington,* U.S.S. *Saratoga,* U.S.S. *Ranger,* U.S.S. *Enterprise,* U.S.S. *Wasp,* U.S.S. *Curtis,* U.S.S. *Albemarle* and U.S.S. *Cincinnati.* This radar had an excellent reputation and every one that did not go down in action with the enemy received an honorable discharge after long and dependable service.

The year 1941 ended with Radar a proved Naval Weapon. There followed a period of feverish effort to improve the performance of Radar in every characteristic and to enlarge its application to every phase of Naval Warfare. Specialization in design for different applications was pursued to develop radars for Surface Search of the Sea as well as Air Search. Great strides were made in the development of many types of cathode ray tube indicators to present radar-derived information to the eye. By the end of

Figure 9.—Radar (Search and Fire Control) and Radio Antennas on the Island of an Aircraft Carrier.

1942 the need for radar had been demonstrated to such degree that the policy was "Get it out at all costs".

The problem of controlling and directing fighter aircraft to intercept enemy bombers developed early in the war. Late in 1943, the Navy installed its first height-finding radar on a large carrier for fighter direction. Half of these first shipboard height finding radars were sent to Great Britain.

The installation of surface and air search radars on submarines greatly increased their offensive power. These submarine radar installations presented many electrical and mechanical problems in providing water tight integrity.

As research in radar continued during the war many new refinements were developed in features of design and construction that previously had given trouble and caused outages. A large number of artifices were developed to render radars less sensitive to the detrimental effects of purposeful jamming radiations of enemy countermeasures equipment. Widely diversified frequencies were employed for their peculiar advantages in special applications. Research activities in radar

continued to increase through 1944 and 1945 even though Radar had reached the stage of technology and engineering design.

The wartime developments in radar have constituted a tremendous economic impetus to the post-war period of the electronics industry. A large number of radar techniques were directly applicable to television and many of the radar trained engineers and technicians have found employment in the television industry. A great variety of electronic computing machines are now being developed using many techniques developed for radar.

The benefits of Navy Radar experience were directly realized in the formulation of the U. S. Coast Guard minimum requirements for Merchant Marine Radar. As a result of these high performance standards, which are now being met by U. S. Commercial Merchant Marine radar manufacturers, this nation's inland and ocean-going vessels have no peer in navigational radar equipment. Aside from the obvious benefits to navigation and piloting, radar serves as a valuable anti-collision device, provides a means for locating approaching weather disturbances, and speeds up shipping especially in normally fog-bound areas. Extensive use is made of radar techniques in a new electronic land surveying device. This precision instrument is particularly useful for rapid mapping operations in mountainous terrain.

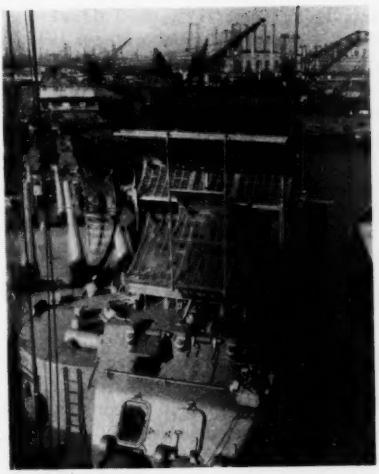


Figure 10.—War-time Fire Control Radar Antennas Aboard a Battleship.

IFF

With the advent of radar and its military applications, some means had to be found to identify each target as friend or enemy. Equipment was developed which operated in conjunction with a parent surface radar. This equipment could interrogate transponders (replying equipment) carried in friendly planes and ships and could receive their replies. The replies would then be correlated with the corresponding radar targets to indicate the friends. This type of equipment was called "IFF" meaning "Identification Friend or Foe".

In the latter part of 1941 the Navy saw the urgency of equipping the fleet with IFF having universal application among the U. S. Forces and its allies. Utilizing British laboratory developments, the Navy developed equipment models, which were put into mass production in a very limited period of time. By November 1942 delivery of airborne equipments had reached 15,000 per month with a proportionate quantity of ground equipments also being produced. An appreciable percentage of the airborne equipments produced was supplied by the Navy to the U. S. Army Air Forces and both airborne and ground equipment was supplied to the British.

To promote research on IFF and to develop a new system to replace the one in use, a Combined Research Group

was established early in 1943 at the Naval Research Laboratory. This group was composed of technical personnel from the Navy and Army and our Allies. The Navy administered this group and was given the responsibility for design and production of the new system.

The IFF program of the Navy resulted in many developments and improvements in the electronics field of components, circuit techniques, packaging, production and standardization.

The Navy is continuing to take an active part in the development of an improved IFF system which should play an important role in the defense of this country.

ELECTRONIC AIDS TO NAVIGATION

The Navy has steadfastly pioneered in the development of electronic aids to navigation for marine and aircraft use. World War II provided considerable impetus to the development of new navigation systems with greater accurracy than was available in the prewar period. Several of these systems, which during the war were cloaked in secrecy, have now been released for the use of civil activities.

Early in 1942, the Army and Navy were called into conference with the National Defense Research Council to consider the potentialities of work at the Massachusetts Institute of Technology Radiation Laboratory on a system of long range navigation which has since become known as LORAN. In this system, three or four powerful radio transmitters, placed in the proper geographical relation emit radio signals which can be utilized to produce a navigational grid providing accurate position information to ships and aircraft. The grid covers an area of some one million square miles per group of three transmitting stations. The Navy was assigned the responsibility for the design and production of transmitting stations and marine receiving equipment. Loran equipment produced by the Navy was installed on a worldwide basis during the war. Although a reduction in loran facilities was dictated by economic factors after the war, loran facilities now operated and maintained by the Coast Guard furnish navigational coverage to major sea and air lanes of the northern hemisphere. These facilities are widely used by civil aviation and marine activities. Loran receivers of commercial design are available, today, as a result of the production engineering by the Navy on military equipment. Loran receivers are now installed aboard transoceanic ships and aircraft. Extensive use of loran is being made by the commercial fishing fleets.

Another electronic aid to navigation pioneered by the Navy is the radar beacon. Development of the radar beacon came as a direct outgrowth of work on the IFF system. The development of radar beacon equipment was commenced by the Navy in January 1942. The first equipment model was delivered to the Naval Research Laboratory in April 1942 for test. Radar beacons provide navigational information to ships and aircraft equipped with radars. Propagation of signals at radar frequencies is limited to line-of-sight distances, which for shipboard installations may be from ten to thirty miles, depending upon the height of the shipboard radar antenna and the radar beacon antenna installed along the coast. Radar beacon service to ships is provided in coastwise and harbor navigation. In the field of air navigation, where line-of-sight may extend to two or three hundred miles, radar beacons have more to offer. Complementary radar beacon equipment now

under development will be installed extensively as an aid to navigation for aircraft. Navy radar beacons will prove extremely useful in furnishing air navigational information to those civil aircraft carrying radar equipment for observing terrain clearance and the detection and avoidance of storms. The Navy took an active part in developing an *Instrument Landing System* (ILS), predecessor to the system now installed at more than ninety civil airports. During 1933, at a time when little effort was being devoted to this work by civil agencies, the Navy initiated the development of a blind landing aid for aircraft carrier installation. In July 1935, a Navy pilot made a completely blind landing on the U.S.S. *Langley*. This remarkable feat provided considerable impetus to the development of the localizer—glidepath type instrument landing system. ILS transmitters developed by the Navy were modified for use as a radio homing beacon and have been widely installed by the Coast Guard and Civil Aeronautics Administration (CAA). The CAA is operating these homing beacons for use as a landing aid while the Coast Guard is operating the same type beacon on weather ships stationed along the Atlantic and Pacific airlanes. These beacons, an outgrowth of the Navy's ILS program, are in constant use by all transoceanic airlines as an aid to air navigation.

G. C. A.

With the outbreak of World War II, it became apparent that U. S. Navy planes would have to operate from bases all over the world. Many of these bases were in areas where almost continuous bad weather prevails, such as, Alaska, the Aleutians, and Newfoundland. It was obvious that one of the highest priority military requirements must be a flexible, accurate blindlanding system for combat aircraft.

In August 1941, radar was introduced as a possible solution to the blind landing problem. It was reasoned that if radar was sufficiently accurate to control anti-aircraft gunfire, it would be sufficiently accurate to assist in aircraft landing by determining the plane's linear deviation in azimuth and elevation from the perfect glidepath in space. At that time, it was decided that the "talk-down" technique should be used and the name Ground Controlled Landing, (GCL), was established. This was later changed to Ground Controlled Approach, (GCA), to more accurately describe the system's function.

Early tests were conducted by the Radiation Laboratory group at Naval Aviation Activities. After three months of preliminary tests using a Gun Laying radar, the gear was moved to Naval Air Station, Quonset Point, Rhode Island, in March 1942. There, after a few weeks of practice, the windshield of a plane was made opaque and the first GCA "instrument" approach landing was made. Later, two Navy PBY's were caught in a snowstorm while trying to land at Quonset Point. They were landed successfully by the GCA radar. Repetition of this story throughout the Navy heightened interest in radar as a landing aid. Further tests that spring at Naval Auxiliary Air Station, Oceana, Virginia, proved that the "talk-down" technique was feasible but that the use of a gun laying radar was impractical. Special equipment was required designed to perform this exacting function.

In May 1942, the entire project moved back to the Radiation Laboratory where the group went to work to

design a radar system solely for ground controlled approach work. This equipment became the forerunner of the wartime GCA. It combined search and traffic control radar with very high precision radar and incorporated its own communication system. Further tests at NAS Quonset Point and at NAAS, Charlestown, R. I., convinced Radiation Laboratories' engineers that the design was sound. At Quonset Point, on December 22, 1942, the first completely blind landing was made using GCA for approach control.

A fullscale military demonstration was held in Washington in February 1943. This demonstration was deemed successful. Fullscale equipment production was initiated by the military services in May 1943. Naval officers and enlisted personnel were assigned the task of establishing a coordinated GCA maintenance and operational training school. A temporary school for instructor training was established at Long Beach, California, in December 1943, and the first commercially built GCA was operated by a Navy crew at Lomita Flight Strip near Los Angeles, California, in February and March 1944.

During the next year, the first production equipments were accepted and placed in service by the Navy. By August 1945, over twenty-five GCA equipments were in use from North Africa to the South Pacific. In the early postwar period, the locations of operating units were changed so that the Naval Reserve training centers, important Naval Air Stations and the NATS (Naval Air Transport Service) would be served best. In a directive dated 7 March 1946, the Chief of Naval Operations designated GCA as the only standard Navy low approach aid, thus making the Navy the first agency to adopt GCA as its primary terminal area navigational aid.

The Naval Air Transport Service (NATS) used GCA exclusively as a bad weather landing aid, and in the years 1945, 1946, 1947, established new records in regard to safety of passengers and percentage of schedules flown. During 1946 the NATS "Hot-shot" flying one flight daily in each direction between San Francisco and Washington, D. C., had but one cancellation in 730 flights! The record of NATS is a proud chapter in Navy history and its success was due in a great measure to the use of GCA equipment at all terminal areas.

In September 1946, the Navy completed the first fixed GCA installation at NAS, Quonset Point, R. I. This installation consisted of permanent cabling from antenna sites to a master control and indicator room in the air station control tower. Installations of this type are contemplated for all permanent Naval Air Stations.

Operating experience with war time equipment has led the Navy to develop new GCA units designed to do an even better job in the future. The use of special techniques to separate aircraft echoes from radar ground echoes will be incorporated in the new units. This adaptation of GCA methods to landings aboard aircraft carriers is now almost completed. The Civil Aeronautics Administration will soon begin installation of fixed GCA equipments based upon the Navy's experience in many of the larger civilian airports in this country.

Navy electronics developments as an aid to aircraft landing not only has strengthened the striking force of Naval Air Power but has given civil aviation an important tool in its progress towards all weather flying.

UNDERWATER SOUND

It has long been conceded that the influence of Navy electronic development work is reflected in many economic fields. In no field, however, has this influence been felt more strongly than in that of underwater acoustics. The results of the Navy's efforts in this field have had far greater consequences in the nation's overall welfare, than the development of military equipment of sufficient technical excellence to bring about the defeat of the greatest enemy submarine fleets in history.

The application of underwater acoustics to commercial activities was extremely limited during the years immediately following World War I. Because of this limitation, few commercial activities were attracted to the field, and progress of the art was slow. Sound, however, remained one of the most effective methods for the propagation of energy under water. This fact, coupled with the part played by the crude listening equipment used in defeating the German Submarine in the first World War, justified the continued interest on the part of the Navy, which encouraged research and development by commercial firms as well as in the naval laboratories and universities of the nation.

Throughout World War I, the Navy's major investigations were made at its experimental station at New London, Connecticut. Important techniques were developed there, most of which, however, were too late to be utilized in the war. In 1919, these problems were transferred to the Naval Engineering Experiment Station at Annapolis. Here the first depth-finder utilizing principles of underwater sound was developed. Some of the first systems were constructed by the Washington Navy Yard, and were installed for the first time on naval vessels. In 1923, the problems were transferred to the Naval Research Laboratory, Bellevue, D. C., where they remained until the beginning of World War II.

Figure 11.—Bottom Core Sampler Being Lowered During Lake Meade Sedimentation Studies by the U.S. Navy Electronics Laboratory and the U.S. Department of Interior.

By 1939, the Navy, assisted by a few old-line companies and universities, had developed the art sufficiently to assure its role in the impending war. When the United States indicated its intention of supporting the cause of the Allies, the interest in finding an effective method of locating submerged submarines grew tremendously. Prominent scientists, including Nobel prize winners, were recruited to study every phase of the problem. Numberless experiments proved that sound waves were the only effective method for propagating signals through the ocean. Other propagation methods, including visible light, infra-red, ultra-violet, and radio waves of any frequency were virtually useless. Scientific and engin-

eering efforts were therefore concentrated on further development of the Navy's existing underwater sound equipment.

Eventually, twenty-three universities and several hundred commercial firms were engaged in the development and production of this equipment. The descriptive word SONAR (*SO*und, *Na*vigation *A*nd *R*anging) was coined in 1943, to describe more adequately Navy applications of its underwater sound equipments. The electronics techniques employed in Sonar are similar in principle to those employed in radar. Direct Navy sonar contracts in force reached a peak of almost 200 million dollars during 1943 and early 1944. This does not include large contracts of the National Defense Research Committee and the University of California Division of War Research for sonar and associated electronics developments. The contributions of the U. S. Navy Electronics Laboratory, San Diego, California and the U. S. Navy Underwater Sound Laboratory, New London, Connecticut in this and related electronics developments are of great importance.

This extensive activity has had a permanent influence on the participants. There can be no doubt that many smaller companies enjoy the benefits of scientific staffs built up during this period by the need of delivering complicated acoustical equipment. Portions of the research laboratories of many great industrial concerns and universities have since been supported and kept active by the Navy's interest in the problems of underwater sound.

From this work, and from the knowledge gained by the great number of persons who have participated in the sonar program, has resulted many developments which have greatly increased the application of acoustics to non-military uses. Naval equipments have been lifted bodily to perform civilian functions. For example, the depth-finder, in addition to its normal use as a navigational aid, is used extensively by fishing vessels to locate schools of fish, and by the Department of Interior and the Army engineers in studying the sedimentation in our man-made and natural lakes. Bathythermographs find a new use by the Bureau of Fisheries to study the effects of the temperature structure of the ocean on the habits of certain species of fish.

Navy-supported oceanographic research at Woods Hole Oceanographic Institution, Woods Hole, Massachusetts and Scripps Institute of Oceanography, La Jolla, California have directly and indirectly contributed to improving the nation's economy. Increased knowledge of the ocean has given us better means of predicting fishing possibilities, of weather forecasting, of establishing trade routes, as well as providing additional scientific knowledge of the earth's history and impending future.

The principles of the generation of intense sound energy perfected over many years by Navy-sponsored activities, are finding an ever-increasing civilian application in the homogenization of milk, aging of beverages, and scientific experimentation designed to provide the means for better living by our people. Control of soot and smoke from factory chimneys may someday be accomplished by use of a sound generator.

One of the oustanding examples of a direct Navy contribution to the national welfare and defense is the recent Lake Meade Sedimentation Survey. This project was conducted in conjunction with the Department of Interior and was directed by Naval personnel, both military and civilian. The survey was begun in 1947 and the sedimentation phase completed in 1949. Results obtained indicated that, at the present rate of sedimentation, the useful life of the Lake Meade installation will be 120 years. It also brought to light information which will enable the Interior Department, Bureau of Reclamation and Geological Survey to ex-

tend the useful life of Lake Meade installations by an estimated additional 100 years. The public and private investments for power, irrigation and water supply dependent upon Lake Meade exceed $500,000,000.00.

Additional work now underway will enable accurate prediction and possible control of water evaporation losses. If calculated results are obtained, sufficient water can be saved to irrigate another western area larger than the Imperial Valley in California. Once again Navy electronics knowledge and equipment are contributing to save untold millions of dollars.

INFRARED

The Navy first seriously studied the application of infrared techniques for signalling in 1918. History records that the forerunner of this technique was investigated by the Navy during the Civil War, but the effort was not pursued to a fruitful end. In 1918, the problem of enemy interception of radio and visual signals was sufficiently serious to warrant investigation of the use of invisible radiation for signalling purposes. A mechanically modulated acetylene search light with an infrared filter and a selenium type photocell receiver was installed aboard the U.S.S. *Pennsylvania.* Morse code messages were transmitted over short ranges, but the bulkiness and unreliability of the equipment resulted in the project being dropped.

In 1930 the Naval Research Laboratory developed an ultraviolet signalling system which was effective over short ranges. This ultra-violet source was invisible to the unaided eye.

The Radio Corporation of America developed an infrared image tube in connection with its television experimentation in 1933. This tube was the forerunner of the types developed for the Navy. During 1935 a telescope utilizing an infrared image tube was demonstrated to the Navy for signalling and reconnaissance purposes. A complete infrared signalling system incorporating these advances was delivered to the Navy for trial in 1939. It was evident that many improvements would be needed to make this equipment suitable for shipboard use. However, the development gave first real evidence that infrared techniques could be utilized effectively by the Navy.

With the formation of the National Defense Research Committee during the summer of 1940, tremendous impetus was given to the prosecution of research in the infrared field. The Navy formulated a research program in infrared and the work was carried on by more than thirty University research groups and industrial firms. These projects covered optical materials, black body and gaseous sources, infrared storage phosphors, image tubes, bolometers, thermopiles, photoconductive cells, and the propagation of infrared energy through the atmosphere. The Navy planned to utilize the unique properties of infrared radiation in the design of short range communication, reconnaissance, recognition, navigation, search, fire control and missile guidance devices.

At the time of the North African invasion, the progress in the development of infrared sources, filters, optics and phosphors, was such that it was feasible to utilize infrared equipment as a means of communication during this amphibious' operation.

In 1943, the Bureau of Ships established an infrared test station at the entrance to the Delaware Bay on the Fort Miles Reservation at Lewes, Delaware. By means of the shore facility thus established, it was possible to evaluate developmental infrared equipment models prior to manufacture

in quantity. Because of its proximity to deep water, this facility permitted adequate test and evaluation of infrared equipment designed for ship to ship and ship to shore use. Other Navy facilities for the test of infrared equipment were the Naval Air Station, Patuxent, Maryland, and the Amphibious Bases at Solomon Island, Maryland, Little Creek, Virginia and Fort Pierce, Florida.

Among the naval developments in the field of infrared during the war were equipments designed for voice transmission, teletype transmission and Morse code transmission. All naval vessels operating in the Pacific during World War II were equipped with Morse code infrared signalling equipment for night-time use during periods of radio silence. Voice and teletype transmission using infrared techniques have proved reliable for distances out to the horizon.

A supply of homing and recognition kits using infrared equipment was provided to underwater demolition teams and small beach assault groups for Pacific amphibious operations.

An infrared device was developed to give range and bearing information on friendly vessels as an aid to ship station keeping during night-time periods of radio and radar silence. Several celestial navigation devices are now under development, one of which is capable of tracking the sun during complete overcast of the sky.

One of the most important uses of infrared techniques to the Navy is the detection and tracking of enemy ships, planes and guided missiles. A suitable heat sensitive element together with its ancillary optical system will detect an object because of the difference in temperature of the object and the ambient temperature. The development of high gain, low noise level amplifiers suitable for this purpose are finding many applications in civilian life, particularly in such fields as medical diagnosis, electronic computing devices, mechanical noise analysis devices and communication equipment. Photoconductive cells developed by the Navy are being used for industrial control, high speed spectral analysis of gases and fluids, sound motion pictures and related recording and reproduction applications, as well as in astronomical research. Certain phases of the image tube research show great promise in the field of fluoroscopy. Without doubt, the greatest contribution has been the gain in theoretical knowledge and technical skill by a great number of American scientists whose peacetime efforts are now being devoted to research and development for the purpose of providing a better way of American life.

RADIAC INSTRUMENTS

Radio activity was first discovered by H. Becquerel in 1896, and was manifest by the blackening of photographic plates by the uranium minerals. Thus, the first instrument for detecting radioactivity made use of the fact that the tracks of individual particles passing through matter may be observed in photographic emulsions.

Radioactive substances give rise to three types of "radiation". These are alpha particles, (high speed ionized helium atoms) beta particles, (high speed electrons) and gamma rays, (electromagnetic radiations.) The ability of radio active substances to ionize gases is of the greatest scientific importance, for many radiological detection instruments utilize this phenomenon in one way or another.

It is well known that considerable artificial radioactivity is created and persists in the neighborhood of an atomic bomb explosion. To evaluate

the radiological hazard involved to personnel necessitates the use of suitable instruments. As mentioned earlier, a photographic plate may be employed for the purpose, but more often the phenomenon of ionization of gases by atomic radiation is utilized as the fundamental principle of the detection instrument. Examples of such instruments include the electroscope, the ionization chamber, the Wilson cloud chamber, and the Geiger-Muller counter. Another detection instrument worthy of mention is the scintillation counter. One can actually see the bright flash of light a high speed alpha particle makes when it strikes a fluorescent screen, consisting, for example, of a piece of glass coated with zinc sulphide.

Radioactivity detection instruments are now called radiac instruments. Radiac is a coined word meaning *R*adio *A*ctivity *D*etection *I*dentification *A*nd *C*omputation. Such instruments permit personnel to determine when it is safe to enter a contaminated area and how long one may remain without permanent injury to health. Radiac instruments are useful for detecting radioactivity in water or food supplies.

A radiac instrument development program was initiated by the Navy to provide portable instruments for operation at high levels of radioactivity under field service conditions. This program was mandatory because available radiac instruments were designed for operation at low levels of radioactivity and under controlled laboratory conditions.

During the early part of World War II a radiac research and development program was inaugurated at the Naval Research Laboratory. The technical accomplishments of the laboratory in this field resulted in several different types of radiac instruments suitable for mass production.

A radiological research laboratory has been established at Hunter's Point, California, to determine what constitutes a radiological hazard, develop techniques and methods for measuring these hazards, and set up parameters of measurement to determine the physiological effect of nuclear radiation.

In the event of an atomic war civilian defense groups will require radiac instruments for mapping "hot areas" so that the public may avoid them. In the meantime such instruments are useful as research tools in laboratories devoted to research in atomic physics. Radiac equipment is presently being used by persons engaged in prospecting for uranium metals!

METEOROLOGICAL ELECTRONIC AIDS

Although numerous aerological techniques and instrumentation advances applicable to predicting surface weather conditions were introduced by the Navy between the years 1920 and 1936. it was only at the close of this period that the possibility of electronics techniques as applied to meteorology became apparent. This was brought about by the need for new methods to cope with the problem of obtaining accurate weather data to insure greater safety in air navigation.

Prior to the development of radiosonde equipment, forecasts were predicated on ground observations and personal observations made by pilots during flight. Later, some forecasts were based upon data obtained from weather instruments installed aboard aircraft. Limiting factors were high cost, restriction of flight altitude and the grounding of planes due to bad weather. Accurate weather data is of the utmost importance during bad weather conditions, therefore some

Figure 12.—Balloon-borne Radiosonde Transmitter for Measuring Atmospheric Pressure, Temperature and Moisture Content.

answer to this problem was urgently needed.

The Navy pioneered in the field of the application of electronics techniques to weather observations. As early as 1936 the Navy developed the first American type radiosonde system. This weather observation equipment embodied a free balloon-borne transmitter (radiosonde) capable of transmitting data with respect to atmospheric pressure, temperature and relative humidity from the earth's surface to altitudes exceeding 50,000 feet. This intelligence was telemetered from the electronic equipment suspended by the observation balloon to a specially designed recording receiver installed at the ground station or aboard ship. This receiver was capable of receiving the transmission from the observation balloon transmitter and permanently recording the transmission for study and evaluation by Navy aerological experts. The first naval electronic weather observation facility placed in regular scheduled operation was located at the Naval Air Station, Anacostia, D. C. This installation was followed in November, 1938 with comparable installations aboard the U.S.S. *California* and the U.S.S. *Lexington.*

Although the preceding technique proved highly satisfactory, numerous instrumentation problems involving the meteorological sensing elements were found to require further research and development. The early radiosondes had used a bimetal strip element to measure temperature. Later, an electrolytic element was developed for use in radiosonde circuits. As a result of research during World War II other highly important advancements were made in this field. A ceramic temperature element was developed for temperature measurement and was found to be far more dependable than its predecessors. During these years improvements were also made in the humidity sensing elements. Originally, radiosondes had employed a hair hygrometer. These were replaced by newly developed hygroscopic salt elements of the cylindrical and strip types. The pressure elements utilized an evacuated aneroid diaphragm which has been improved vastly in recent years by the addition of temperature compensation features.

The electronic weather observation techniques originated by the Navy are widely used by the military services. This Navy developed equipment also assists the Weather Bureau in the preparation of its day to day as well as long range weather forecasting which are so vital to commercial airlines,

Figure 13.—Automatic Tracking Radiosonde Receiving Antenna.

commercial interests, and the public at large.

In addition to the above technological advances in the field of meteorology, the Navy has also played a vital role in pioneering the development of three types of automatic weather stations. A project for the development of an automatic weather station was undertaken in 1939. This station was designed for unattended operation. Its function was to broadcast indications of pressure, temperature, relative humidity, rainfall, wind direction and wind speed. The instruments, except those exposed to the weather, were housed in a small shelter. The meteorological measurements were coded at the transmitting station into a series of slow pulses, from which the actual data could be recovered and recorded at a remote point.

A parachute type of automatic weather station was developed in early 1941. It was intended for use in remote and inaccessible areas to transmit weather data for a relatively short period of time. This expendable equipment required special design in order to protect it against landing shock because the equipment was designed to be dropped from a plane in flight.

A buoy type automatic weather station, designed for oceanic weather observations, reached a practical stage of development in 1944. This equipment was designed to transmit atmospheric pressure, air and water temperatures, wind speed and wind direction.

Other meteorological electronic aids developed by the Navy included radio wind sounding equpiment, radar wind sounding reflectors, radar wind sounding pulse repeaters, and equipment for the measurement of cloud ceilings.

ELECTRONIC COUNTERMEASURES

The perfection of new weapons for national defense is one of the most important and spectacular tasks of the military forces. With the advent of each new weapon an equally important task must be accomplished—that of finding a countermeasure. For example, the gas mask was developed to counter the use of poison gas and the anti-aircraft gun was developed when the airplane became a weapon of war.

As electronic equipment grew in importance as a means of communication (radio); for detecting objects at a distance (radar), and for control of guided missiles, a new military art has evolved. Each of these devices has a countermeasure which, if used properly, will deny to the enemy the effective use of his weapons. This art is known simply as Electronic Countermeasures.

A radar set transmits a short, powerful pulse of radio energy. When this energy strikes an object, such as a ship or a plane, a very small amount of it is reflected. This small echo is detected and amplified at the originating radar set by use of an extremely sensitive receiver. Since the transmitted power is so much greater than that reflected, a receiver at the target location tuned to the frequency of the distant radar will detect the radar transmitter at a much greater range than the radar receiver can detect the echo returned from the target. Thus, a submarine with an intercept receiver can ascertain when a radar-equipped plane is searching for it long before the plane can locate the submarine. In World War II, this type of warning saved many submarines from attack by planes. Also, a "noise" transmitter located at the target can be made to completely obscure the radio echo. Another weakness of radar is that it cannot discern details of the target, i.e., its resolution is not as good as the resolution of a television receiver for

example. As a result of this, small inexpensive devices can be made to simulate a plane or ship, thus confusing the radar operator. For example, a few ounces of aluminum cut into thin strips of the proper length, when thrown free into the air will appear to the radar as though the object were a large plane. This type of aluminum foil material was used in great quantities during World War II and came to be known by the code name "Window". These are only a few of the weaknesses of electronic devices that can be exploited by the intelligent use of electronic countermeasures.

When the United States entered World War II, thousands of German radar sites defended the continental empire of the Third Reich. There were chains of long-range stations to give the enemy early warning of the approach of Allied bombers and to enable him to plot the position of our formations as well as their course and speed while enroute to the target. As we, the Germans had airborne radars which enabled the German fighters to locate and attack our aircraft at night. Still other kinds of radar were used to direct searchlights as well as anti-aircraft guns. The German Navy was similarly equipped. As time passed, chains of sea watching radars covered the entire Atlantic and Mediterranean coast of the continent. Japanese radar, at the start of the war, was far behind that of the Allies or of Germany. However, both in quantity and quality Japanese radar improved until by the end of the war it represented a formidable obstacle to our forces in the Pacific.

Prior to the war, research work of a long-range character had been carried on in the Naval Research Laboratory. After Pearl Harbor, it became clear that if the enemy's radar was as useful to him as we expected our own would be to us, it would be necessary to put a major effort into development of countermeasures against specific German and Japanese equipments. This feeling was reinforced by the experience of the British, who had already used countermeasures successfully in the defense of their homeland and had attached a high and increasing importance to this activity. The effective use of electronic countermeasures was a major contributing factor to the winning of the Battle of Britain.

In the realization that an expanded research and development program would be required, the Navy initiated action which led to the establishment of the Radio Research Laboratory at Harvard University. This laboratory, under the management of the National Defense Research Council, conducted a large proportion of the countermeasures research and development work for the military services. From this laboratory and from Navy laboratories came the equipment and techniques required to wage a successful electronic countermeasures war against the enemy.

Electronic countermeasures equipment capable of intercepting enemy radar and radio transmissions was installed in surface ships, submarines, and aircraft.

In the Pacific, Japanese use of radar was almost completely nullified by Navy electronics countermeasures. Their radar equipped planes were jammed whenever they approached Navy ships, forcing them to use less accurate visual means of launching torpedoes and bombs and in many cases the jamming so confused them that attack was completely abandoned. In one instance, a Navy submarine intercepted radar signals from three Japanese submarines. These signals were followed to their source and the three submarines were sunk! Navy submarines also made excellent use of their intercept receivers to evade Japanese radar equipped planes.

In Europe, the Navy took a large part in the electronic jamming war against the German radars along the

invasion coasts, blinding the "eyes" of the Germans so as to assist our troops to get ashore at Salerno, Normandy, and in southern France.

The war time research and development work sparked by the Navy's requirement for electronic countermeasures represents a very considerable contribution to the radio art from which the public benefits directly. Tunable receivers were designed which are capable of continuous frequency coverage into frequency regions many times as high as those attained by any prewar commercial equipment. Transmitters operable over unprecedentedly wide frequency ranges and power output were developed. Tubes of special characteristics, embodying entirely new principles, were designed and produced in order to make many of these transmitters possible. Unusual antennas, capable of operating over wide frequency ranges without adjustment, presented another difficult problem which was successfully solved.

Since it is conceivable that future electronic equipment may operate in any portion of the electronmagnetic frequency spectrum from the audio range to ultra-violet light frequencies, and employ any type of modulation, new techniques must be evolved for countermeasures work. Older methods are being extended to new limits and entirely new techniques developed to perform this task. Transmitters and receivers that will cover large portions of the spectrum without mechanical scanning are required.

THE BUILDING BLOCKS
(COMPONENT PARTS)

The large number of electronic devices developed since the inception of wireless communication has been the result of almost unlimited application of scientific and practical talent to the problems of electronic principles and circuitry. In the process of designing equipment to fulfill military requirements, physicists and electronics engineers have provided a wealth of fundamental information. One of the more promising paths to better, more dependable, longer lasting equipment for both civil and military use is the improvement of the component parts used in building the equipment. Having learned to design and build a house, we look for better bricks, steel beams, roofing and foundation materials; having learned to design and build electronic equipment, we look for better resistors, capacitors and inductors, switches, relays, sockets, insulators and transformers, to mention but a few. These are the fundamentals of electronic circuits. By definition, a component part is an item which is supplied, procured, stocked and issued as a unit and which is not amenable to further extensive disassembly. These building blocks are designed to perform a specified function in a given electronics circuit and are combined into equipments and systems ranging from a proximity fuse weighing but a few ounces to the most complicated radar system weighing many tons.

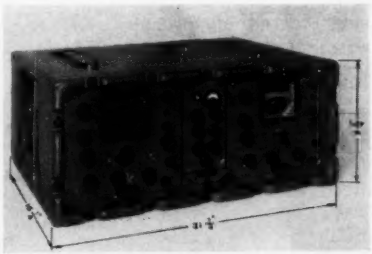


Figure 14.—Miniaturized General Purpose Communications Receiver.

Electronic equipment used by the Navy must operate properly and remain dependable under a variety of severe conditions. These conditions are not ordinarily encountered in any other single field of government or industry. Electronics equipment for Navy and Marine Corps use must be designed to withstand the shock of gun fire, salt water spray, tropical heat, high humidity, fungus growth, sand blast, bomb shock and similar rigorous operating conditions; it must be light in weight and be of minimum physical size. Marine Corps electronics equipment must be buoyant and submersion proof and must withstand the special conditions imposed by its tactical use in amphibious operations. Transportability of this class of equipment poses special design problems. Electronics equipment installed aboard a Navy plane is required to operate in cold rarefied air above 50,000 feet within minutes after the plane takes off from an aircraft carrier operating in tropical waters. Guided missile electronics equipment must operate dependably under high accelerations and extreme changes of temperature.

As industry, working under Navy Contract, developed electronics components meeting these stringent requirements, the methods for producing them economically in quantity were developed. The home broadcast receiver today performs better and is considerably smaller in size and is subject to fewer failures than early receivers principally because of the improvements of component parts. Thus, the public ultimately benefits from Navy efforts to obtain better building blocks for its electronic equipment.

One of the high priority endeavors of the Navy in the field of electronics is that of miniaturization. The term "miniaturization" considered literally may be misleading as to intent. As used here, this term means the greatest possible reduction in the size and weight of electronic equipment commensurate with retaining the necessary equipment characteristics of reliability, high operating stability, ease of maintenance, safety to personnel, reasonable length of useful equipment life, reasonable production cost and suitable designs to incorporate general-usage packaged sub-assemblies.

The miniaturization of circuit component parts and the development of miniature packaged sub-assemblies are not only vital for shipboard electronic equipment, but are well nigh indispensable in the fields of guided missiles, proximity fuses, electronic computers, test equipment, and controls for aircraft including those distinct from radio and radar.

The design and installation of Navy high power, low frequency stations during the period 1920 to 1930 posed many difficult component parts problems. For example, the Navy Department, working with insulator manufacturers, had to develop antenna suspension insulators capable of supporting antenna structures weighing as much as 30 tons and capable of withstanding radio frequency voltages as high as 300,000 volts. Navy design improvements, including improved porcelains, endcap cements, and insulator glazes resulted from the development of these early Navy type radio insulators. These design improvements were later employed effectively to produce reliable power line insulators for public utility use.

The development of radar equipment during World War II accelerated the need for flexible, solid-dielectric radio frequency cables. To meet this requirement the Navy initiated the necessary action to establish two large industrial plants for the production of polyethylene plastic. This development was commenced in 1942. Today, this same material, polyethylene, is used in the manufacturing of radio frequency lines used with television receivers and other types of commercial radio equipment. Polyethylene is also widely used

for refrigerator ice trays which remain flexible at freezing temperatures; for bags to package many foods, and hundreds of other useful articles for the home.

It is not possible within the confines of several pages or even several chapters to describe in any detail the vast and comprehensive work of the Navy Department during the period from about 1910 to 1949 in relation to 125 distinct categories of electronic circuit component parts. It must suffice to say that many of these Navy developed items such as radio frequency connectors, waveguides and fittings, waveguide switches, delay lines, directional couplers, echo boxes, attenuators, rotary joints, coaxial relays, hermetically sealed power and audio transformers, glass dielectric capacitors, molded phenolic cased mica dielectric capacitors, tube sockets, and dependable high quality composition resistors have not only permitted the improvement of Navy electronic equipment, but also of commercial electronic equipment, now available for public use.

ELECTRON TUBES

Electron tubes of appropriate design perform such important functions as: converting alternating current to pulsating direct current; converting direct current to alternating current of any frequency (within limits); amplifying alternating currents of any frequency (within limits); extracting intelligence from modulated waves; converting electrical impulses into visual displays; converting light impulses into electrical signals, to mention a few. The constant improvement of existing types of tubes, and the evolvement of new types has been of prime concern to the Navy since the two element and three element vacuum tube came into general use prior to World War I.

During the early years of radio broadcasting, particularly between 1921 and 1935, there was a rapid growth of highly competitive tube industry. These years saw the appearance of a multiplicity of receiving tube types. Their utility weakness resulted from lack of standardization and interchangeability. About 1935 the Navy started a program to remedy this chaotic situation.

Military requirements were stated for various types of tubes by promulgation of technical specifications. In order to be acceptable for Navy use, an electron tube must pass prescribed performance qualification tests. Through the establishment and maintenance of these test standards, the

Figure 15.—Miniaturized Packaged Subassembly Plug-in Type Employing Encapsulated Circuit (multivibrator). This Subassembly Provides Approximately 5 to 1 Weight and Space Reduction Over Conventional Chassis Construction and Makes Possible More Rapid and More Economical Maintenance of Electronics Equipment.

Figure 16.—Modern High Power Pulsed Magnetron Capable of Delivering 600 Kilowatts for a Maximum Duration of 6 Microseconds. The Assembled Tube (measuring approximately 12½ inches by 6 inches overall) and its Component Parts are Shown.

Navy has helped bring about standardization of the electron tube industry. This was an achievement of no little economic and logistic importance. It provided the electron tube industry with a common language and intelligible technical standards. The advent of World War II brought about such a tremendous increase in the demand for electron tubes that the expanded industry was sorely taxed to meet military requirements. But for the earlier effort of the Navy in standardization, electron tubes of required characteristics could never have been produced in quantities necessary to prosecute the war.

In order to concentrate production on a relatively few electron tube types, and to simplify stocking and electronics equipment maintenance problems, the Navy prepared a "preferred list" of electron tubes. Care was taken to insure that tubes having the fundamental and mechanical characteristics so indispensable to the development of a wide variety of electronics equipment were included on this list.

The Navy's program to "ruggedize" electron tubes began in 1944. The purpose of this program is to increase the dependability of tubes by improving their mechanical (structural) characteristics. The benefits of this program accrue not only to the Navy in carrying out its national defense mission, but the general public is the great benefactor through improved electronic equipments for home, school, industry, and the myriad of applications of electronics that benefit our people in their day to day life.

When miniature electron tubes were introduced by industry for use in portable battery powered broadcast receivers, the Navy recognized their potential advantages in saving of space, weight, and power requirements. These

early miniature electron tubes were unsatisfactory for military equipment because of lack of mechanical strength and lack of uniform electrical characteristics. In 1943, the Navy, cooperating with the War Production Board, put forth a vigorous effort to develop miniature tubes suitable for military purposes. This program was so successful that miniature electron tubes are now the preferred tubes for use in a large percentage of the electronics equipment being designed today, both for military and civilian use. In order to achieve further reduction in size and weight of electronics equipment, the Navy is sponsoring development of sub-miniature tubes. Success in electron tube sub-miniaturization is the key to further reductions in weight and space requirements of electronics equipment.

These improvement programs have created electron tubes useful for critical applications in radar, sonar, electronic navigation, missile guidance, fire control and television equipment.

The Navy played a very important role in the development of electron tubes for special purposes. Typical of such electron tubes applications are found in FM broadcasting, television and radar. The Navy was one of the early pioneers in the development of magnetrons, klystrons, lighthouse tubes, resnatrons, and gas switching tubes. The Navy is sponsoring or participating in the development of other classes of electron tubes, including the travelling wave tube (high gain broad band amplifying tube), storage tube (a memory device) and transistors (an amplifier or oscillator resistance device).

The advent of atomic warfare has created the problem of protecting our citizens from the hazards of atomic radiation. Electronic devices designed to detect radiation of this character must be made available in such quantity as to provide reasonable protection to every man, woman and child. At this date the most widely used device for radiation detection is the Geiger Counter. The heart of this equipment is an electron tube. In 1947, the Navy initiated a program to standardize electron tubes for this class of equipment. The purpose of this program is to provide maximum civilian and military utility of these equipments in case of emergency.

During World War II the Navy financed facilities for large scale production of electron tubes. This policy was necessary in order to provide these vital war materials in sufficient quantity to prosecute the war to victory. It was realized that these facilities could be converted readily to peacetime production after the cessation of hostilities. Their peacetime product would contribute to the higher American standard of living through the medium of inexpensive, high quality electron tubes for use in the American home and American industry. Experience proves that this Navy policy was in the best interests of the nation.

CRYSTALS

The ever increasing demand for communication frequencies has necessitated the development of precision frequency control equipment to insure that a radio transmitter shall maintain close adherence to its assigned operating frequency. This is necessary to reduce to a minimum interference between two stations operating on adjacent channels.

Piezo electric crystals offer one solution to the problem of frequency control. Crystal controlled oscillators are widely used in radio transmitting

equipment. Crystals are also employed in precision frequency standard equipment. The Navy was a pioneer in the use of crystals (in lieu of electrically driven tuning forks, for example) for frequency calibration work. By 1924 the Navy was utilizing quartz crystals for the control of ship and shore station high frequency transmitters. Later crystal controlled "fixed frequency" receivers were developed by the Navy and are presently used throughout the Naval Communication System.

By 1940 sufficient data had been collected by the Navy to show that as a piezo electric crystal ages its resonant frequency changes. To remedy this operating deficiency, a technique of etching and heat treatment of crystals was incorporated in crystal manufacturing processes.

Before 1944, the Navy had developed a miniaturized crystal capable of frequency stability of approximately .005% accuracy. The prime value of this development lay in the fact that this miniature crystal could be mass produced economically.

One of the recent outstanding developments is a small metal glass sealed holder for crystals. The introduction of this holder enables a crystal to operate in a reliable manner even when subjected to extreme variations in temperature and humidity.

Everyone has seen clocks marked "Naval Observatory Time" in railroad stations, telegraph offices, jewelry stores and other public places where time accuracy is important. The public has learned to rely upon Navy time standards. The basis of the Navy clock which controls this service is a crystal controlled electronics device located at the Naval observatory.

TEST EQUIPMENT

Electronics test equipment is required for the maintenance and operation of electronics equipment. The more common types of test equipment include frequency meters, radio frequency and audio frequency oscillators, tube testers and instruments to measure voltage, current, power, resistance, inductance and capacity.

The Navy has long maintained leadership in accurate frequency control devices and has consistently placed great emphasis on precise frequency measuring equipment. Not long after the year 1920 the Navy used oscillating quartz crystals to establish standards for frequency measurement. This was followed by the development of heterodyne frequency meters covering ranges up to 30 megacycles per second. Beginning in 1930 and in subsequent years, the Navy pioneered in the development of portable frequency meters. Then followed the decade or synthesizer type of frequency motor which was used as a calibrator of frequencies. At the present time, the Naval Shore Establishment is being equipped with a precision frequency monitoring equipment. This equipment is of such high accuracy that were it used to drive an electric clock the clock would maintain an accuracy of one second in three years (on a short time measurement basis)!

As a companion to the frequency meter, the Navy developed accurately calibrated sources of radio frequency power. This work was begun in the late 1920's. Signal generators, as they are called, are valuable tools in determining the performance of electronic circuits. They have been progressively improved during the past twenty years. One of the related important advances the Navy sponsored was in developing a series of broad band signal generators covering frequency ranges from 100 megacycles per second to higher frequencies.

With the advent of radar as a detection device, it became imperative that equipment be developed to check the performance of radar and provide an indication of the distance the radar "sees". In 1942, a Navy scientist conceived and developed a phantom target which fulfilled these requirements. During the war, the Navy further improved this device. It is now known as an "echo box".

The Navy recognized the need for adequate test equipment of all types at the time the electronic industry was in its infancy. It diligently prosecuted a program of developing tube testers, oscilloscopes, test meters, bridges, and other test equipment. The experience of the Navy's technical personnel has been made available to industry and has made possible many of the great strides the commercial field has made in providing accurate, well constructed test instruments.

ELECTROMAGNETIC WAVE PROPAGATION

To predict, for example, the performance of a radio circuit comprising a radio transmitter located some distance from a receiver, or alternatively the range of a radar set, necessitates considerable knowledge of the propagation of radio waves in the atmosphere of the earth.

By 1923 the Navy was engaged in exploring the possibility of using short waves for long distance communication work. These frequencies were commonly accepted at that time as unsuitable for commercial or military transmissions. Subsequent Navy investigations of the propagation characteristics of high frequency radio waves proved that early theories regarding the utility of these frequencies were unfounded. On the contrary, this region in the electromagnetic spectrum is now more important to electronics than the purchase of Manhattan Island (for the sum of $24.00) is to the modern New Yorker.

Characteristics of the ionosphere were being explored by the Navy as early as 1925. One result of this study was the discovery of skip distance phenomenon. A second result was the discovery that the properties of the ionosphere vary in a predictable manner. Modern high frequency wave propagation theory is predicated in part on these discoveries. This theory is useful for predicting what frequency is best suited at a given time of day for radio communication between two or more specified points. Incident to studies in this field then being conducted at the Naval Research Laboratory it was discovered that a ship passing through the path of high frequency radio waves causes a shadow effect. Later investigations of this phenomenon at the same laboratory foreshadowed the very important military detection equipment known as radar. Prior to the start of World War II, the Navy conducted extensive tests using very low frequencies to determine some of their propagation characteristics. The purpose of this study was to determine what frequencies must be employed to realize world wide communication coverage.

The Navy's fundamental investigations in the theory of propagation of electromagnetic radiation greatly assisted the nation's commercial communication services and expedited the rapid growth of the radio industry. The Navy furnished the radio equipment and personnel on various polar expeditions, and made valuable studies relating to the propagation of radio waves in these regions. The Navy is continuing to investigate all phases of wave propagation at all frequencies in use and is sponsoring research work to extend the frontiers of knowledge concerning wave propagation phenomenon through the entire electromagnetic spectrum.

RADIO INTERFERENCE

Interference is any electrical disturbance which causes undesired responses or the malfunctioning of electronic equipments. Sources of interference include generators, motors, gasoline engines, electrical contracts, fluorescent lamps, rectifiers, certain medical apparatus, industrial heating, and many mechanical devices. The elimination of radio interference, or its reduction to a minimum is an operational requirement for all equipment procured and used by the Navy. It is of importance to observe that for the same signal to noise ratio at the receiving location a reduction of noise by 3 decibels means that the power of the transmitter may be halved.

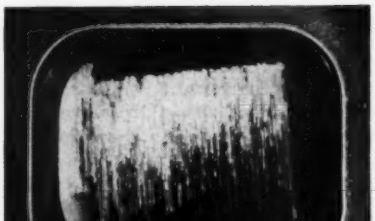


Figure 17.—Man-made Electrical Interference as it Appears on a Radar Scope.

A survey of ship to shore communications in 1934 disclosed that man-made electrical noise was creating major interference to communication receivers and the first systematic attempt to reduce these interferences was made by Navy engineers and the Tobe Deutschmann Company.

The first interference survey conducted aboard ship took place in 1938 on the carrier U.S.S. *Yorktown*. About four years prior to the advent of World War II a program was initiated to develop electronic equipment capable of measuring radio interference caused by electrical and mechanical devices. The Navy recognized generators and ignition systems to be prolific sources of electrical noise and took steps to remedy the condition. In 1940, limits of allowable radio noise and standards of measurement were defined and a systematic approach made to render all equipment at Naval activities and on shipboard interference—free.

In 1945, the Navy developed a radio interference measuring equipment capable of measuring radio noise in the frequency range 100 to 400 megacycles per second. As the frequency ranges of electronics equipment were extended to higher and higher frequencies, in 1948 the Navy started the development of radio interference measuring equipment covering these higher frequencies.

Television and radio are disrupted by man made electrical noise.

The Navy's effort in this field has set a high standard for industry—the achievement of which has led to better television and radio reception in the American home.

CONCLUSION

The important point to understand about an effective electronics program is that it is a continuously growing endeavor. It is never possible or safe to say, "we have reached a leveling off position in relation to electronic research and development." We must always assume that any potential enemy is also bending every effort to devise more effective electronic techniques applicable to more lethal weapons. To assume less is sheer folly!

We can never afford the luxury of gambling with our national security. We can never relinquish the lead gained in the field of electronics. To maintain this lead is and will remain a costly and difficult undertaking. But experience dictates that this has been one of our most profitable national investments.

We are devising weapons with unheard of lethel power. But we have yet to devise means of delivering these weapons economically in large quantities over long distances, at high speeds and laying them accurately on restricted targets. It is felt these means must be accomplished by applications of electronics techniques.

Whether or not the Navy succeeds in obtaining funds and facilities to achieve electronic research and developments which are indispensable to its mission depends largely upon whether the Navy can convince American citizens that what the Navy is doing, or intends to do, in the electronic field is also vital to the public. In fostering such a policy, the Navy intends to refrain from the pretence that Navy preferences alone are a sufficient justification for appealing to the citizen for support even though such support is paramount. A strong Navy means a strong America. The Navy helps insure world peace.

Navy electronics will thrive by its ever increasing applications to the comfort, education and protection of the American citizen. Electronics fortunately is expanding in an age when new strategic tasks make unusual demands on the potentialities electronics possesses. This era creates special opportunities for the exercise of its unique capabilities; and the American people are liberal in recognizing its merits. A more abundant life—or total disaster? These are the only two alternatives. Electronics research and development is the deciding factor—it is the keystone of our national security!

ACKNOWLEDGMENT

The authors wish to express appreciation to their colleagues in the Electronics Design and Development Division, Bureau of Ships, Navy Department, for their cooperation in assisting in the preparation of plans for this work. The writers especially desire to mention the outstanding contributions of Mr. Robert H. Jones, Senior Radar Design Engineer; Mr. George B. Cummings, Senior Sonar Design Engineer; and Mr. John N. Hall, Senior Components Design Engineer. In addition, the authors are indebted to Mr. Hall for his careful review of the manuscript.

Official Armed Services Photograph

Showing a portion of one of the Navy's great shore establishments at Mare Island Naval Shipyard, Vallejo, California. An important support of the active Fleet—an invaluable asset if mobilization becomes necessary.

BUOYANCY CHARACTERISTICS

A Study of the Rate of Water Absorption and Buoyancy Retention Characteristics of Cellular Hard Rubber, Phenolic Foam and Balsa Wood

H. J. STARK, J. ALPERT AND T. L. SHOEMAKER

THE AUTHORS

H. J. STARK graduated from Lawrence College of Wisconsin in 1933 and holds a Batchelor of Arts degree. From 1935-36 pursued graduate work in Chemistry at George Washington University, Washington, D. C. Employed as a research and analytical chemist at the Naval Research Laboratory, Anacostia, D. C. from 1937 to 1940. Entered Military Service with the Army Air Forces in 1940 serving in the New Guinea, Leyte and Luzon Campaigns in the Southwest Pacific area. Returned to civilian life in 1946 continuing his civilian scientific pursuits for the Navy Department in the plastics section of the Bureau of Ships where he is now employed as a Materials Engineer.

He is a member of the Society of Plastics Engineers, Alpha Chi Sigma, Kappa Kappa Psi, Horological Institute of America, Reserve Officers Association, American Legion, Washington Rubber Group and The Ancient Order of the Deep.

JEROME ALPERT received the degree of B.S. in Chemistry at New York University in 1933. Worked at short term positions from 1933-1935 such as instructor in chemistry at an adult evening high school, laboratory aide in a drug manufacturing plant and as an assistant on the advertising staff of a daily newspaper. Appointed as junior scientific aide at the Industrial Testing Laboratory of the Philadelphia Naval Shipyard in Aug. 1935. Worked from 1935 to 1940 on chemical inspection of a variety of materials including ferrous and non ferrous alloys, tars, asphalts, textiles, saponifiable and non saponifiable oils, soaps, miscellaneous chemicals etc. From 1940 to the present time, on developmental projects involving insecticides, various phases of toxicology and flotation materials. Present title Technologist (General).

TOM L. SHOEMAKER received the degree of B.S. in Chemistry from the University of Pittsburg, 1933. Worked in chemical warfare developments (gases and gas masks) to 1937. Worked as a metallurgical inspector in a steel mill to 1940. Appointed as civilian chemist at Industrial Testing Laboratory of the Philadelphia Naval Shipyard in 1940. From 1940 to 1943 worked on chemical inspection of ferrous and non ferrous alloys. From 1943 to date has engaged in developmental work on wood preservatives, wood and life floats.

Showing a portion of one of the Navy's great shore establishments at Mare Island Naval Shipyard, Vallejo, California. An important support of the active Fleet—an invaluable asset if mobilization becomes necessary.

BUOYANCY CHARACTERISTICS

INTRODUCTION

A new synthetic cellular plastic material was proposed to the Bureau of Ships for use as a buoyant material in applications involving flotation gear. The material is commercially known as phenolic foam and several industrial manufacturers are currently engaged in producing the material.

One of the applications for which this material was proposed involved the replacement of balsa wood as the prime flotation substance. The particular application wherein the material might be used was one of considerable importance in that if the buoyant properties of the material exceeded a minimum requirement very serious consequences were apt to follow. Little information was available concerning the buoyancy properties of phenolic foam and even less information comparing the buoyant properties of phenolic foam with balsa wood or any other cellular buoyant material.

Because of this lack of information and a desire to consider phenolic foam as a buoyant material and the intriguing potential of great labor saving if the material could be used; to this end these tests were conducted.

It is proposed to publish at a later date a description of an operation wherein two large void spaces on a naval vessel were filled with comparative ease and success with phenolic foam.

SUMMARY

This article compares the rate of water absorption within a 24 hour period for 3 low density cellular materials when immersed in water under two different water pressures or heads. The actual buoyancy remaining in these materials up to 24 hours under the same conditions is also shown. Curves depicting water absorption and retained buoyancy plotted against time graphically show the results of test.

Phenolic foam, cellular hard rubber and balsa wood are the materials tested. 3 different densities of phenolic foam (1.9, 2.6 and 8.8 pounds per cubic foot) were used. Cellular hard rubber and balsa wood having average densities of 6.9 and 8.9 pounds per cubic foot respectively were used in the tests.

Significant conclusions drawn from the tests are (a) that cellular hard rubber is superior to the other two materials tested in rate of water pick up and retention of buoyancy, (b) the rate of water pick-up and retention of buoyancy for the phenolic foams and balsa wood are fairly similar, and (c) the buoyancy retention of the lighter density (1.9 pounds per cubic foot) is slightly higher than balsa wood and the other two densities of phenolic foam.

OBJECTIVE

The object of this investigation was to determine the relative rate within a 24 hour period in which three different low density cellular materials would absorb water when immersed in water under two different water pressures. It was also decided to determine the relative buoyancy remaining in the material within the 24 hour period under two different water pressures.

BUOYANCY CHARACTERISTICS

MATERIALS

Three different low density cellular materials were selected for test. The density of the three materials were selected so that their densities would be quite similar. It was not possible to select materials that would have identical densities. The greatest variation between the three materials in the similar density range is 2 pounds per cubic foot, i.e. cellular hard rubber of 6.9 and balsa wood of 8.9.

In addition to this, two lower densities of the phenolic foam were selected.

Phenolic Foam

It was desired to test phenolic foam in the following density ranges; 1-3, 3-5 and 6-10 pounds per cubic foot. The densities of these materials tested were 1.9, 2.6 and 8.8 pounds per cubic foot after removal of the heavy skin or rind. The apparent densities of the materials in the "as received" condition with the skin or rind on them was higher. As an example; the intermediate density material with the rind was 5.5 pounds per cubic foot but when the skin was removed its density was 2.6 pounds per cubic foot.

Table I—Densities

Material	Original apparent density (dry)
Phenolic Foam D	1.9
Phenolic Foam G	2.6
Phenolic Foam E	8.8
Balsa Wood	8.9
Cellular Hard Rubber	6.9

The phenolic foams tested were commercial grades of material obtained from the manufacture. The foams for test were not made in the Government Laboratory.

Cellular Hard Rubber

This material was obtained from Navy's standard stock and conformed to the Navy's specification number 33B3, "Buoyancy Material, Hard, Cellular, Rubber". After removal of the rind, the apparent density of this material was 6.9 pounds per cubic foot.

Balsa Wood

The balsa wood used was obtained from Navy stock. The average density of the balsa wood was 8.9 pounds per cubic foot. Test specimens were cut from the stock with the grain of the wood running in the direction of the long dimension so as to expose as little of the end grain as possible.

Table No. 1 lists the densities of various materials used and the designation given to the phenolic foams.

It is noted that the cellular hard rubber and phenolic foams were tested without any skin or rind on them thus making for a more severe condition than if the materials had been tested with skin or rinds on them. The balsa wood was tested under optimum conditions i.e. little end grain exposed.

METHOD OF TEST

All specimens used conformed to one size, namely, 1¼ by 1¼ by 3 inches. Samples were run in triplicate for the foams. Ten specimens of balsa wood were used in ten different densities for each test.

Specimens of all materials were weighed in the dry condition and then immersed together in a small laboratory tank under a definite head of water in a standpipe attached to the tank. One set of specimens was immersed under a 20 foot head of water for 24 hours and another set under a 30 foot head for the same period of time. The immersion in each case was

interrupted at the end of 2, 4, 8, 12, 16, 18 and 24 hours to determine the rates of water absorption. The time required for weighing at each interval was approximately one-half hour. The specimens were actually under the head of water for a full 24 hours. Each specimen at each weighing was allowed to drain for five seconds.

DISCUSSION OF RESULTS

The results of the rate of water absorption tests under 20 and 30 foot heads are shown in Figures 1 and 2 respectively. The percent by weight of water absorbed (on the basis of the original dry weight of the specimen) is plotted against time.

The order of effectiveness of the various materials is shown in Table No. 2. The figures shown are actual weights of water absorbed by the specimens tested. Each specimen was approximately 4.7 cubic inches.

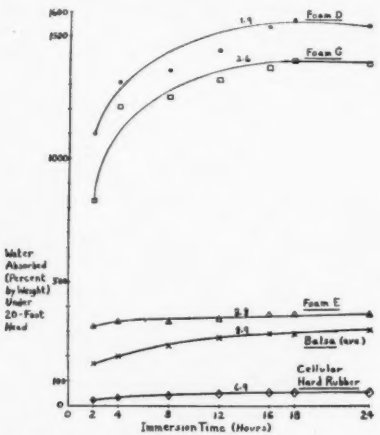


Figure 1

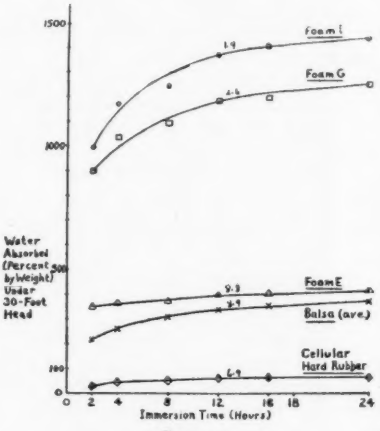


Figure 2

Table No. 2.—Water Absorbed During Immersion.

Material	Initial dry weight (grams)	Water absorbed during 24 hr. immersion (grams)	
		20 ft. head	30 ft. head
Cellular hard rubber	8.6	4.7	5.9
Phenolic foam D	2.4	37.	36.
Balsa wood	10.9	34.	40.
Phenolic foam G	3.2	43.	43.
Phenolic foam E	11.2	43.	46.

The cellular hard rubber appeared to have a very low rate of water absorption. After two hours immersion it absorbed about 25% and increased to only 50% after 24 hours.

The rates of water absorption for balsa wood and phenolic foam E are considerably higher on a percentage basis but are similar or of the same order of magnitude.

The rates for the two very low densities of phenolic foam G and D are very high on a percentage basis as was expected.

A better picture of anticipated performance of these materials is obtained if this data is interpreted in terms of buoyancy remaining in the material after test. This is best shown in Table number 3 and Figures 3 and 4. In Table No. 3 the materials are listed in their respective order of effectiveness.

It is observed that the cellular hard rubber retained the highest amount of buoyancy. The lowest density phenolic foam was next best and the second lowest density phenolic foam third best while balsa wood rated fourth. Phenolic foam E rated fifth. It is significant to point out that the lowest density phenolic foam absorbed less water and retained higher buoyancy than the higher density phenolic foams. There is no apparent explanation for this phenomena and it appeared contrary to usual expectations.

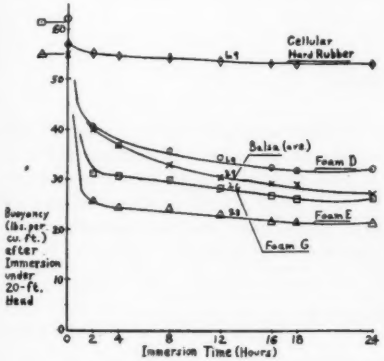


Figure 3

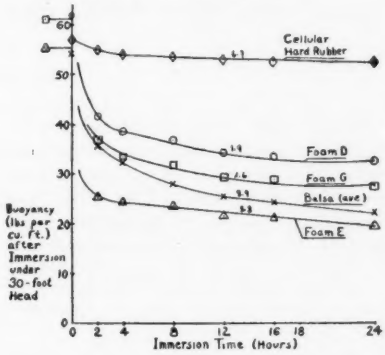


Figure 4

Table No. 3.—Buoyancy (Salt Water) After Immersion.

Material	Original apparent density (dry) (lbs/cu. ft.)	Buoyancy after 24 hrs. immersion (lbs/cu. ft.)	
		20 ft. head	30 ft. head
Cellular hard rubber	6.9	53.3	52.5
Phenolic Foam D	1.9	32.3	32.7
Phenolic Foam G	2.6	26.4	27.6
Balsa Wood	8.9	27.1	22.4
Phenolic Foam E	8.8	21.5	19.5

BUOYANCY CHARACTERISTICS

It is seen from Figures 3 and 4 that the rate of retention of buoyancy for cellular hard rubber is very good. The rates of retention of buoyancy for the 3 phenolic foams and balsa wood are in the same range. Phenolic foam D being the best.

It is seen from Figures 3 and 4 that greatest loss of buoyancy takes place within the first eight hours of test.

This discussion has not dealt with the fact that tests were run under two different water pressure heads. It is observed that the results obtained when testing the afore mentioned materials under a 30 foot head are very close to those obtained when testing under a 20 foot head.

The balsa wood specimens were selected over a range of densities from 6 to 12 pounds per cubic foot and varied considerably in water absorption as was anticipated. In general the lighter specimens absorbed somewhat more water than the heavier ones however the final weights after 24 hours immersion were nearly the same.

While these tests were initially undertaken to determine the relative rates of water absorption of the various materials, these percentage values can be misleading in interpreting this data because the initial weights of the various materials differed considerably.

The figures pertaining to buoyancy remaining after immersion are a better measure of anticipated service performance of these materials.

CONCLUSIONS

These tests were performed essentially to obtain data comparing the rates of water pick up for the various materials mentioned. This data was deemed necessary in connection with certain Naval applications of buoyant materials where the rate of water pick up is one of several important factors.

The general conclusions drawn have already been stated in the summary of this article and are not repeated here in the conclusions.

ACKNOWLEDGMENT

The authors desire to acknowledge the assistance of Commander W. E. Pittman, Superintendent of the Industrial Test Laboratory, Philadelphia Naval Shipyard, Philadelphia, Pa.

It is also desired to acknowledge the assistance rendered by Mr. K. L. Proctor and Mr. H. L. Katz of the Chemical Division of the Industrial Test Laboratory of the Philadelphia Naval Shipyard. The interest of these two individuals in one of these materials has led to its utilization in a service installation. This installation will be the subject of another report to be prepared at a later date.

FURNACE EXIT TEMPERATURES

A Method for Determining Furnace Exit Temperatures and Absorption Rates in Oil Fired Marine Boilers

JENS T. HOLM

THE AUTHOR

The writer was born in Copenhagen, Denmark in 1919 and came to the United States at the age of four. He graduated from Webb Institute of Naval Architecture in 1941 and went on active duty as an Ensign, CC(U)S, U.S.N.R. He returned to inactive duty with the rank of Lt. Cdr. in 1945 and after a short period of time with the New York Shipbuilding Corp., was appointed Professor of Marine Engineering at Webb Institute, which position he now holds.

In the design of marine steam power plants, the designer today is rarely called upon to design the various units. However, he is often called upon to check these designs. He must determine that the units he plans to use are well suited for their purpose and will operate well with a minimum of maintenance. To aid in this work, various criteria of service are often used. Many of these criteria however, are not dimensionless and must be used with extreme caution.

In the field of marine boilers, the methods and criteria often used are hopelessly outmoded. Many engineers still use equivalent evaporation per square foot of heating surface as a criterion of boiler service conditions, not realizing that such a criterion is nearly worthless in attempting to establish the operating characteristics of modern boilers, as will be shown later in the paper.

Very obviously, peak temperatures of tubes, refractories and gases are indices of operating conditions and loading. In any boiler, the maximum temperature existing anywhere is the flame temperature in the furnace. The actual value of this temperature is very difficult to determine but fortunately it

is not important in the study of operating conditions. This temperature exists only well within the flame itself, in very limited areas and no part of the boiler or furnace is exposed to this temperature. The really determining factor in the operating conditions is the temperature of the gases leaving the furnace. This temperature is more readily obtainable and is of great importance as an index of the heat absorbed by the furnace surfaces and the temperatures to which these surfaces are exposed. It can be readily seen that such figures are the true measure of the loading of a boiler. Further, since two boilers of widely varying total heating surface may have the same furnace arrangements and operating temperatures, it follows that they may have very high furnace temperatures and absorption rates and still the boiler with the larger convection generation bank will have the lower equivalent evaporation rate, and would under such a criterion be adjudged the more conservative boiler.

In a boiler furnace, the combustion of the fuel results in a rapid release of heat. However, almost instantaneously, some of this heat is absorbed by the cooled surfaces of the furnace by the phenomena of radiation. When high temperature differences exist between the warm body (the products of combustion) and the cooled surfaces (the furnace water walls and screen tubes) the quantity of heat absorbed is very high, often 30% or more of the total heat released in the furnace by combustion. Radiant heat exchange is practically instantaneous and results in very large exchanges of heat for comparatively small areas. This phenomena of radiant heating can exist only between two surfaces separated by a medium that does not absorb heat by radiation. Thus, once the radiant heat beamed from the furnace interior strikes the tube walls the surface temperature rises and the heat transfer becomes a conduction process resulting in a definite temperature gradient across the tube materials as well as any other coating, such as scale, or the resistance of the water film inside the tubes. As was stated above, the rate of heat transmission by radiation is very high, or another way of saying the same thing is: in a boiler furnace, the rate of heat absorption by the cooled surfaces is very high. So long as the tubes are clean, the high absorption rate is not generally unacceptable since it does not result in excessive tube temperatures. However, the presence of a comparatively thin layer of scale inside the water wall and screen tubes may well result in excessive metal temperatures.

This fact points up the necessity for clean tubes and good feed water and also imposes a limit on acceptable heat absorption rates in the furnace surfaces commensurate with commercially acceptable limits of maximum scale formation and good circulation characteristics.

The calculation of furnace absorption rates is a corallary of the prediction of furnace temperature, for the heat that does not contribute to raising the temperature of the combustion gases must obviously have been absorbed by the watercooled surfaces of the screen and water walls.

It is the object of this paper to present the necessary data and formulas for making these calculations. Presented here is a correlation of existing formulas and data with some empirical constants, to furnish in as simple a manner as possible, a method for estimating furnace absorption rates and exit temperatures so that the marine power plant designer can check and evaluate the furnace design features of proposed boiler installations.

The basic theory of furnace exit temperature calculation consists in determining the quantity of heat given up by the furnace gases and equating it to the heat radiated to the cooled sur-

faces and solving for the furnace exit temperature.

It is well to first review the basic theory of radiant heat transfer as formulated by the Stefan-Boltzman relation. This relation states that the heat transfer between two bodies is proportional to the difference of the fourth powers of their absolute temperatures, or stated in pound, hour, Fahrenheit units:—

$$Q = .172\,A\left[\left(\frac{T}{100}\right)^4 - \left(\frac{T_C}{100}\right)^4\right] F_A\, F_E \qquad \text{(Eq. 1)}$$

where

Q = net heat transferred in B.T.U. per hour

T_F = absolute temperature in degrees Rankine (F. absolute) of the hotter body

T_C = absolute temperature of the cooler body

A = area of one body exposed to or "seeing" the other body

F_A = arrangement factor to correct for arrangement, angularity of faces and relative areas of the two bodies.

F_E = emissivity factor, a function of the emissivities of both bodies.

The emissivity of a body is the ratio of the heat radiated per unit area by a given surface at a given temperature to the heat radiated by a perfect black surface (a perfect radiator) per unit area at the same temperature. The radiation absorptivity is the same as the emissivity at the same temperature. Emissivity and absorptivity vary widely with temperature, particularly for gases.

A boiler furnace varies considerably from the ideal conception of the Stefan-Boltzmann relation. Uncooled surfaces such as refractories are incapable of absorbing heat and must, therefore, reflect their heat back to the furnace gases or to the cooled surface. In further considering the problem it is well to study two opposite extremes, one where all furnace surfaces are water-cooled and the other where no surfaces exposed to the furnace flames are water-cooled. Both of these tyes are very rare but serve to illustrate the problem. An uncooled furnace results in the maximum possible exit temperature for a given firing condition while the completely cooled furnace gives the lowest possible temperature. The ordinary boiler furnace falls somewhere between these two limiting furnace arrangements.

Considering the latter case first, suppose we had a boiler with no water walls and where the screen tubes are shielded from the furnace, i.e., do not "see" the furnace. Then the furnace exit temperature is that due entirely to the sensible heat added by the fuel and air heater to the air or products of combustion.

then

$$t_F = \frac{H + (R\ t_a\ c_a)}{(1 + R)\ c_g} \qquad \text{(Eq. 2)}$$

where

t_F = furnace exit temperature, degrees F.

H = lower heating value of fuel, i.e., the sensible heat, B.T.U. per lb.

R = lbs. of air required per lb. fuel

t_a = temperature, degrees F. of air entering furnace

c_a = mean specific heat of air above zero degrees F.

c_g = mean specific heat of flue gases above zero degrees F.

When a fuel oil of 17,500 B.T.U. per lb. lower heat value is burned with 16 lbs. of air per lb. fuel and an air inlet temperature of 300 degrees F. there will result a furnace exit temperature of 3750 degrees F. This temperature is the maximum furnace exit temperature possible under the given firing conditions and is usually called the "adiabatic" temperature.

Obviously now, the introduction of some cooled surface will result in a lower furnace exit temperature, and

the more cooled surface introduced, the lower will be the furnace exit temperature.

In the boiler furnace with all surfaces water-cooled that are exposed to or "see" the flames, conditions are identical with that of a surface of a body placed inside another surface. In this case, the arrangement factor, F_A given in (Eq. 1) above, is unity. Further, if in (Eq. 1) T_F and T_C are respectively the temperature of the flames and the cooled surface and A the area of the cooled surface, then Q represents the heat absorbed by radiation by the cooled surface. In the average furnace, T_C may be taken as about 100 degrees F. higher than the saturation temperature of the steam without appreciable error, since we are taking the differences of fourth powers and T_F^4 results in a much larger number. Thus, if we know T_F and T_C we can evaluate Q.

The combined emissivity factor F_E is somewhat difficult to determine. It is a function of the emissivities of the cooled surfaces and the gas cloud or flames. The cooled surface emissivity is nearly constant at about 0.9. This is the approximate emissivity of black steel in the range from 100 to 700 degrees F.

The gas cloud or flame is a gaseous burning mixture consisting essentially of glowing fuel and carbon particles and water vapor, carbon dioxide, oxygen and nitrogen. Small amounts of sulfur dioxide, carbon monoxide and other gases may be present but their influence is negligible. The monatomic gases, oxygen and nitrogen have very low emissivities and may also be neglected. This leaves water vapor, carbon dioxide and particles as the sources of radiation from the flames.

Since the gas cloud is made up of radiating particles and gas molecules, it follows that the radiant heat rays may originate from well within the gas cloud. Further, the particles and molecules are somewhat opaque to radiant heat and may absorb heat from sources farther inside the flame. We may make a numerical measure of this probable reabsorption by measuring the concentration of particles and molecules (by their partial pressures) and by measuring the average distance the radiant heat must travel from within the flames to the surface. Generally, it is sufficiently accurate to assume that the flames completely fill the furnace and that the mean free path or mean radiating length is equal to two-thirds the edge of a cube of the same volume as the furnace, or:—

$$L = \tfrac{2}{3}\sqrt[3]{\text{Furnace Vol.}}$$

where

L = mean radiating length, ft.

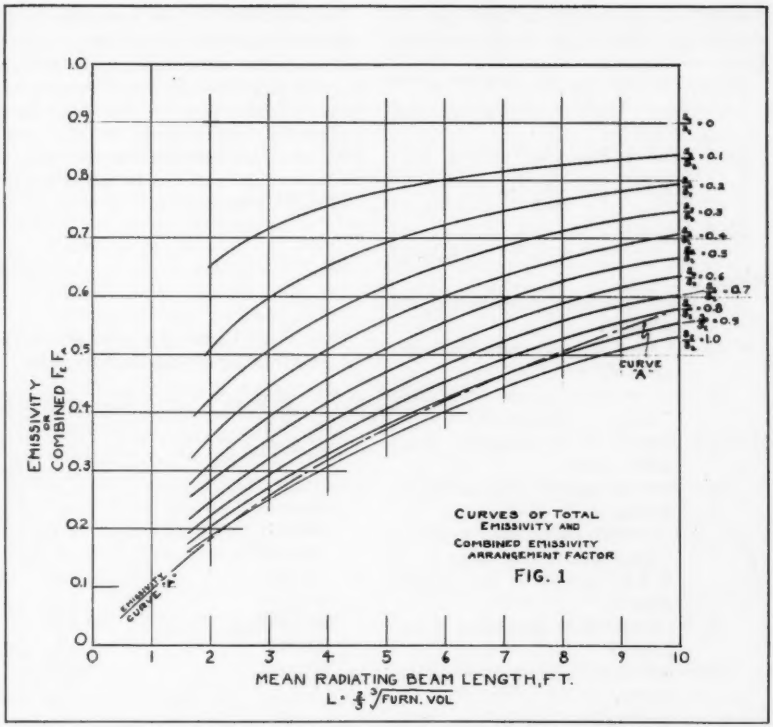
We can state the following general rules governing flame emission:—

(A) Emissivity of radiant gases varies with the partial pressure (i.e. the molecular concentration) of the gas and the mean radiating length.

(B) Emissivity of fuel or soot particles varies with the size and concentration of the particles and the mean radiating length.

Fortunately, most marine boilers are fired with oils of nearly similar characteristics. These residue oils contain approximately 10.5% hydrogen and have a high heat value of about 18,500 B.T.U. per lb. Normally burned with approximately 15% excess air, these fuels result in products of combustion containing about 6% water vapor by weight and 13½% CO_2 by volume in the dried flue gases. The partial pressure of the water vapor present is about .094 atmospheres and for carbon dioxide about .1123 atmospheres. When fired at near normal loads, the furnace and flue gas conditions vary but little from these standards.

Accurate values of the emissivity of the radiant gases have been published by several investigators. Since our flue gases have a nearly constant analysis, we may use the resulting emissivities


EMISSIVITY OR COMBINED F_E
MEAN RADIATING BEAM LENGTH, FT.
$L = \frac{4}{5}\sqrt[3]{\text{FURN. VOL}}$
CURVE A
EMISSIVITY CURVE "F"
CURVES OF TOTAL EMISSIVITY AND COMBINED EMISSIVITY ARRANGEMENT FACTOR
FIG. 1

as constant values, varying only with furnace temperature and mean radiating lengths.

The particle emissivity can be evaluated directly from tests of marine boilers and expanded to cover the range of most marine boilers.

The emissivity of the radiant gases decreases with temperature. The emissivity of the particles increases with temperature. The variations in the two emissivities are such that the total particle and gas emissivity is very nearly independent of temperature for the conditions in normal oil fired marine boilers.

From available data on marine boilers the writer has calculated and plotted curve "'A" on (Fig. 1) a plot of total flame emissivity against mean radiating length, assuming the emissivity to be constant for varying temperatures. This curve is applicable to the problem when firing under the conditions outlined above.

In the example under discussion, the entire interior surface of the furnace is water cooled. In this case, the emissivity factor in (Eq. 1) is given as:—

$$F_E = \frac{1}{\frac{1}{E_C} + \frac{1}{E_F} - 1}$$

where

E_C = cooled surface emissivity

E_F = flame emissivity from curve "A" (Fig. 1)

(Eq. 1) can now be evaluated for a given value of T_F. Further, Q_1, the heat

radiated to the cooled surface must be equal to the heat lost by the furnace gases Q_2 or:—

$$Q_1 = .172\ F_E F_A\ S_C\ [(t_F + 460)^4 - (t_C + 460)^4] + S'_C\ U_C\ (t_F - t_C) + 130\ S_R$$

$$Q_2 = W(H + Rt_a(.243)) - W(R + 1)\ (.247 + .014\ \frac{t_F}{1000})t_F$$

$$Q_1 = Q_2$$

(Eq. 3)

where

t_F = furnace exit temperature degrees F.

t_C = cooled surface temperature degrees F.

$S_C = A$ = area of cooled surface "seeing" flames, sq. ft.

$F_E F_A$ = combined arrangement emissivity factor

S_C' = area of cooled surface excluding screen, sq. ft.

U_C = convection heat transfer rate to cooled surface (see table (1)), B.T.U. per sq. ft. per hr. degrees F.

R = pounds of air per pound of fuel burned

H = low heat value of fuel B.T.U. per lb.

Q_1 = heat radiated from flame, B.T.U. per hr.

Q_2 = heat absorbed by cooled surfaces, B.T.U. per hr.

W = weight of fuel burned in pounds per hr.

t_a = temperature of air entering furnace degrees F.

S_R = area of refractory or uncooled surface in furnace

$.243 = C_a$ mean specific heat of air

$.247 + .014\ \frac{t_F}{1000} = C_g$ = mean specific heat of flue gas

Included in the heat given up to the cooled surface there must also be a small amount given up by direct convection and a small loss through the refractory surfaces. Table (1) gives the approximate convection conductances to the cooled surfaces, U_C. Further, the loss through the refractory surfaces is approximately 130 B.T.U. per sq. ft.

Table (1).—Values of U_C for convection heat transfer to furnace waterwalls.

B.T.U. Release per sq. ft. cold surface	U_C convection conductance per sq. ft. waterwall surface
100,000	.1
200,000	.1
300,000	.1
400,000	.6
500,000	2.5
600,000	8.0
700,000	21.0
800,000	45.0

The curve marked $\frac{S_C}{S_t} = 1$. (Fig. 1), gives the combined emissivity of the fully water-cooled surface that is, it is an evaluation of $F_E = \frac{1}{\frac{1}{E_C} + \frac{1}{E_F} - 1}$ for varying values of mean radiating length.

Let us assume that our totally cooled furnace is operated under the following conditions:—

furnace volume = 1,000 cu. ft.
S_C = cooled surface area = 600 sq. ft.
S_t = total furnace envelope = 600 sq. ft.
S_C' = cooled surface, less screen = 500 sq. ft.
S_R = refractory surface = zero sq. ft.
W = weight of fuel burned per hr. = 2,000 lbs. per hr.
H = low heat value of fuel = 17,500 B.T.U. per lb. fuel oil
t_a = furnace air inlet temperature = 300 degrees F.
R = Pounds air per pound fuel oil = 16

For this example the operating pressure of the boiler is assumed to be 600 lbs. per sq. inch and the corresponding saturation temperature is 488 degrees F. Using a total tube wall temperature gradient of 100 degrees F., there results cold surface temperature of 588 degrees F. U_C may be read from table (1) as .1 then

$$L = \frac{2}{3}\sqrt[3]{1000} = 6.66 \text{ ft. and from (Fig. 1)}$$

$F_E F_A = .426$

Substituting values in (Eq. 1) we can solve for t_F. This is most easily done by evaluating each side of the equation at values of t_F and plotting. The intersection of the two curves is the solution. The solution becomes 2,084 degrees F., see (Fig. 2).

For a furnace of the size and surface given and the firing rate given, this is the lowest possible temperature attainable.

Boiler furnaces of more normal design involving a certain amount of refractory surface as well as cold surface will fall between these two limiting temperatures, that is, between 2,084 degrees F. and 3,750 degrees F.

The combined factor $F_E F_A$ for arrangements of normal boilers is given by the following expression:

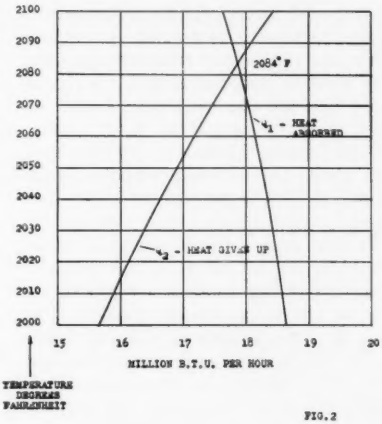


FIG. 2

$$F_E F_A = \frac{1}{\frac{1}{E_C} + \frac{S_C}{S_t}\left(\frac{1}{E_F} - 1\right)} \qquad \text{(Eq. 4)}$$

where

E_C = emissivity or absorptivity of the cooled surface = .9
E_F = total flame emissivity
S_C = total effective cooled surface
S_t = total furnace envelope area "seeing" the flames

As has been noted, E_F is nearly independent of temperature and is a function of radiant length (for normal marine oil fired furnaces). (Eq. 4) has been plotted in (Fig. 1) as a family of curves for varying values of L and $\frac{S_C}{S_t}$. This plot is for the same conditions as outlined for curve "A".

An understanding of what is meant by "effective" water-cooled surface is also important. For walls of tubes tangent or nearly tangent to each other, S_C is only the projected area of the surface. If however, the tubes are more widely spaced, the tubes receive radiation both directly from the flames and indirectly

from the refractory. Table (2) gives correction factors to be applied to surfaces other than the tangent tube arrangement.

It must be understood that the charts given here for use with (Eq. 3, and 4) apply only to normal oil fired marine boilers burning ordinary bunker fuels with about 15% by weight excess air or about 13½% CO_2 by volume in dry flue gases.

To best demonstrate the use of these formulas, let us take an actual problem as an illustrative example. Suppose we have a boiler furnace as illustrated in (Fig. 3). This furnace is fired with 1,500 lbs. of 10% hydrogen oil with a high heat value of 18,500 B.T.U. per lb. and a low heat value of 17,500 B.T.U. per lb. Air enters the burners at 300 degrees F. Including air moisture, combustion results in about 6% by wt. moisture in the combustion products. The boiler pressure is 600 lbs. per sq. inch.

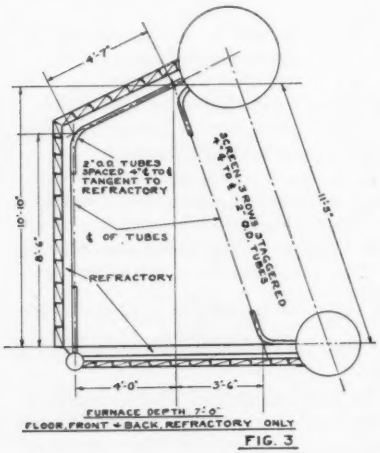


FIG. 3

The projected area of the screen, taken on the tube centerline is:

$11'\text{–}5'' \times 7'\text{–}0'' = 79.8$ sq. ft.

Table (2) gives the factor for deep screen rows as

$f = 1.0$

S_C (screen) $= 79.8 \times 1.0 = 79.8$ sq. ft.

Table (2).—Values of f, effectiveness factors for cooled surfaces in furnaces.

$S_C = A_{WW} \times f_{WW} + A_{SCR} \times f_{SCR}$

where

A_{WW} = area waterwalls

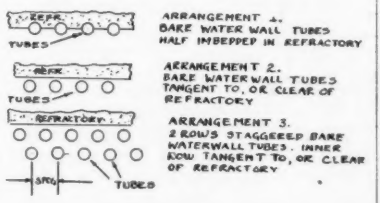
f_{WW} = effectiveness factor for waterwalls

A_{SCR} = area screen

f_{SCR} = effectiveness factor for screen

S_C = total effective cooled surface

Spacing Dia.	f Arrangement 1	f Arrangement 2 or 3	f Arrangement 4
1	1.0	1.0	1.0
1.5	.818	.96	.99
2	.662	.89	.97
2.5	.550	.80	.95
3.0	.470	.72	.91
4.0	.360	.59	.82



Screen rows considered 100% effective or $f = 1$

Fully studded tubes $f = .7$ to $.9$

Partially studded ½ as bare tubes $f = 1.0$

½ as studded tubes

Water cooled floor, refractory covered $f = .1$

For the waterwall side and roof, the projected area $= (8'\text{–}6'' + 4'\text{–}7'') \times 7'\text{–}0'' = 91.6$ sq. ft.

Table (2) gives the factor for tubes tangent to refractory, spaced 4" for 2" tubes as .89

then

S_C (water wall) = $91.6 \times .89 =$ 81.5 sq. ft.

and the total effective cooled surface is

$81.5 + 79.8 = 161.3$ sq. ft.

The floor area is 52.5 sq. ft., the back and front wall area is 57.7 sq. ft.

Then the total furnace envelope is given as:

area back wall	57.7
area front wall	57.7
area floor	52.5
area screen	79.8
area waterwall and roof	91.6
total furnace envelope	339.3 sq. ft.

then

$$\frac{S_C}{S_t} = \frac{161.3}{339.3} = .476$$

and $S_R = S_t - S_C = 178.0$ sq. ft.

and the effective area without the screen 81.5 sq. ft.

The furnace volume is $57.7 \times 7 = 403.9$ cu. ft. and the mean radiating length is

$$L = \frac{2}{3}\sqrt[3]{403.9} = 4.93 \text{ ft.}$$

The release rate per sq. ft. of cooled surface is $\frac{1500 \times 18500}{161.3} = 172{,}000$ B.T. U. per sq. ft. for which, from table (1), $U_C = .1$.

From the values of $\frac{S_C}{S_t}$ and L we read $F_E F_A$ from (Fig. 1) as $F_E F_A = .525$. We can now substitute these values into (Eq. 3), for various values of t_F, assuming $t_C = 490 + 110 = 600$ degrees F. Designating the left hand part of the equation as Q_1 and the right hand portion as Q_2 we have the results in tabular form, listed below:

(1)	flame temperature	2400°F	2450°F	2500°F
(2)	$t_F + 460$	2860	2910	2960
(3)	$t_C + 460$	1060	1060	1060
(4)	$\left(\frac{t_F + 460}{100}\right)^4$	669,000	717,000	767,000
(5)	$\left(\frac{t_C + 460}{100}\right)^4$	12,630	12,630	12,630
(6)	(4) − (5)	656,370	704,370	754,370
(7)	$.172\ F_E\ F_A\ S_C \times$ (6)	9,570,000	10,270,000	11,000,000
(8)	$t_F - t_C$	1800	1850	1900
(9)	$S_C'\ U_C\ (t_F - t_C)$	14,670	15,090	15,500
(10)	$130\ S_R$	23,150	23,150	23,150
(11)	$Q_1 = (7) + (9) + (10)$	9,607,820	10,308,240	11,038,650
(12)	$.247 + .014\frac{t_F}{1000}$	.281	.281	.282
(13)	$Wt_F(R + 1) \times (12)$	17,200,000	17,550,000	17,980,000
(14)	$.243\ Rt_a + H$	18,667	18,667	18,667
(15)	$W(.243\ Rt_a + H)$	28,000,000	28,000,000	28,000,000
(16)	$Q_2 = 13 + 15$	10,800,000	10,450,000	10,020,000

The values of Q_1 and Q_2 are plotted in (Fig. 4); the intersection at 2457 degrees F. is the solution, and this is the furnace exit temperature for the conditions given. From (Fig. 4), we also see that the total heat absorbed was 10,400,000 B.T.U. per Hr. or $\frac{10,400,000}{161.3} = 62,000$ B.T.U. per sq. ft. This is the absorption rate of the furnace per ft. of effective cooled surface.

Recognizing that some parts of the radiating flame mass may be appreciably hotter than the exit temperature, t_F, some designers prefer to use a mean value between the exit temperature and the "adiabatic" temperature as the average flame temperature. This average value is then used instead of the furnace exit temperature t_F in substituting in the basic Stefan-Boltzmann relation. The use of such a mean is, however, highly arbitrary, despite some foundation in fact, and makes the calculation even more laborious. Further, the character of the heat release phenomenon in combustion has never been clearly defined, and lacking a better evalution, it seems better to stick to the known temperature t_F. We must also recognize that some parts of the flame mass may be cooler than the flame exit temperature. Such errors as do appear under this use of t_F, are adequately corrected for by the proper use of a convection heat transfer coefficient, as given in table (1).

For our example, our calculations have indicated a furnace exit temperature of 2457 degress F. and a radiant absorption of 62,000 B.T.U. per sq. ft. per hr. Furnace exit temperatures lower than 2400 degrees F. at normal designed firing rates may result in poor oil ignition, especially when firing

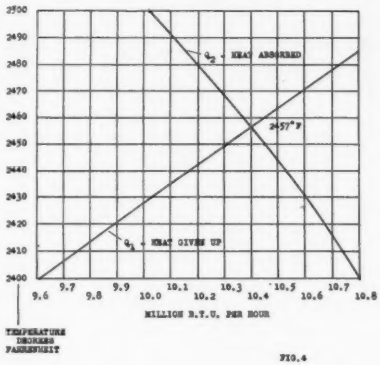


FIG. 4

at reduced rates. Temperatures higher than 3000 degrees F. result in excessive refractory and screen tube temperatures with consequent high refractory and tube maintenance.

Experience with merchant boilers has shown that radiant absorption rates should be kept below 120,000 B.T.U. per sq. ft. of effective cooled surface per hr., for satisfactory maintenance and circulation conditions. However, many satisfactory boiler, including naval boilers, have been built to operate at much higher absorption rates. It must be borne in mind that such higher absorption rates call for lower maximum allowable scale thicknesses, and low resistance circulation paths, that is, an extensive downcomer system.

It cannot be stated that every residue oil will result in the temperatures estimated from these curves and formulas. The results are average figures and experience has indicated that the error is not great. When used to check designs, the radiant absorption rate is the best criterion. If these values are conservative, satisfactory operating conditions can be expected.

A NAVIGATIONAL INSTRUMENT

Presentation of a Recently Developed Navigational Instrument for Determining Headings of a Vessel by Center Ranges

JOHN W. SAWYER

THE AUTHOR

Developed the instrument described during his period of active service as a Reserve Officer in the Navy. Prior to his Naval war service he served for a number of years in the merchant marine. A previous article by the author on a quite different subject appeared in the November 1949 issue of the JOURNAL.

I INTRODUCTION

The problem of determining a vessel's gyro error or magnetic compass deviation is one that frequently confronts the navigators of both naval and merchant vessels. Weather is often no obliging element in simplifying this problem. Poor visibility due to fog, rain or snow frequently makes the satisfactory solution an impossibility.

During the years of World War II carefully scheduled sailings of large numbers of vessels was essential. It was normal practice to adjust the magnetic compasses of these vessels prior to sailing. The loading of magnetic cargo, tanks, steel, and shipyard repair work often caused large deviations that rendered the compass inoperative. The adjustment was readily accomplished provided sights could be taken on celestial bodies. If visibility precluded such sights then it was necessary to resort to the laborious and time consuming methods of ranging.[1] These include: swinging the vessel about or near one point and taking bearings on a distant object;[2] crossing and recrossing a range line such as AC of Figure 1.

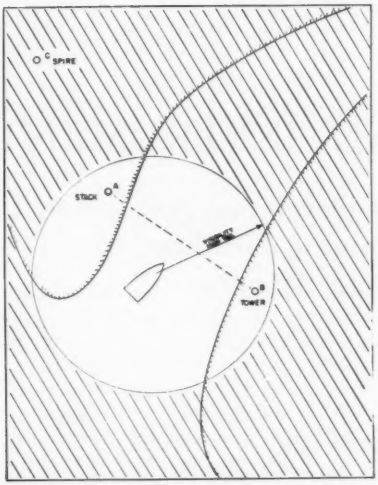


Fig. 1.—Vessel maneuvering in a harbor with visibility limited to 1000 yards. Shaded area indicates range of visibilty.

The latter method of ranging requires that two known points, the bearing of AC is known or can be determined, A and C be located on the same side of the observer or the vessel. Under conditions of poor visibility as indicated by the shading in Figure 1 the range AC is unusable. In this situation there is no means by which the true heading of the vessel could be obtained. Therefore the gyro error or compass deviation could not be computed.

It is readily apparent that under conditions of limited visibility as indicated in Figure 1 true headings of a vessel could be determined if a sight were taken on the range AB. This range is defined as a *center range* since the vessel is between the range objects A and B. While this is referred to as a center range it is emphasized that the sight may be taken at *any* point along AB. The heading of the vessel does not influence the sight. The vessel may or may not be on a course at right angles to the range. Bearing of the line AB may be determined from hydrographic charts. The sight is made by the observer when on the range. At that instant the graduated dial, described later, is so oriented that the zero position is either true or magnetic north.

II DESCRIPTION OF INSTRUMENT

The need for an instrument to determine the true heading of a vessel while crossing a center range became evident after a number of eye straining experiences while ranging in rain and fog. Certain conditions were encountered where work had to be discontinued due to poor visibility.

An instrument, see Figures 2 and 3, has been developed and patented by the Bureau of Ships, Department of the Navy, that would enable an observer on a vessel to take a sight on a center range. Incorporated in the instrument is a graduated dial, 0-360 deg., that is set so as to become automatically oriented with its zero point to true or magnetic north when the observer determines the vessel is on the range.

The instrument consists of three main parts, Figure 2, which are:

1. Reflecting elements with supporting base and pointers.
2. Graduated dial.
3. Adapter plate and lock nut.

The reflecting elements, with aluminized surfaces, are mounted on a common base. They are set with an included angle of approximately 93°. This angle permits light from two diametrically opposed objects such as A and B, Figure 4, one on either side of the observer to strike the mirrors and be reflected to a common point above the apex of the mirrors. The observer can thus see both A and B by placing *one* eye at the proper position.

The pointers are attached to the lower section of the base supporting the mirrors. They extend to the degree markings on the graduated dial when assembled as in Figure 3. An examina-

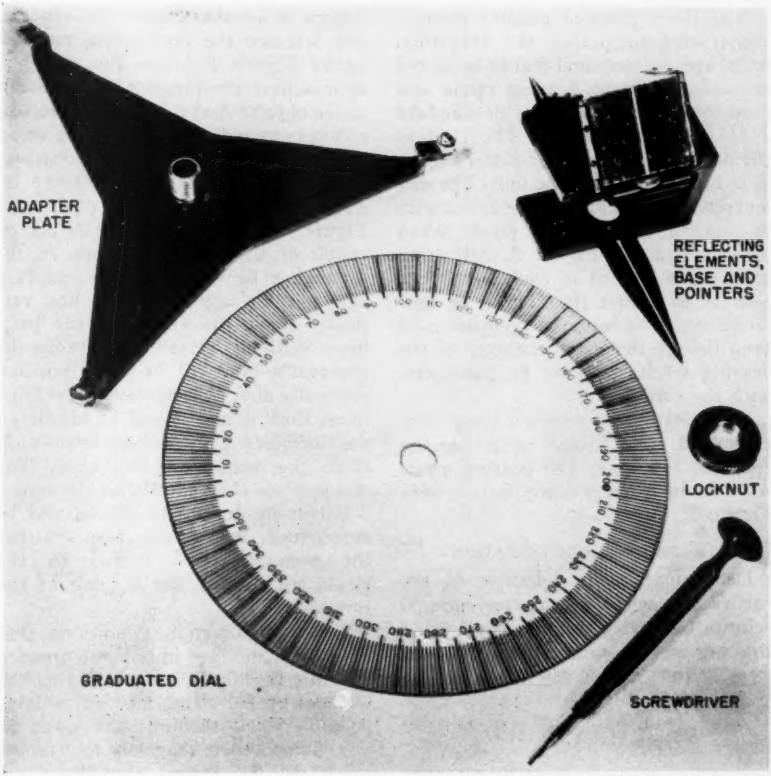


Fig. 2.—Component parts of the instrument.

tion of the mirrors and pointers in Figures 2 and 3 will reveal center lines engraved in each. These lines extend across each mirror and from the base to the end of the pointers. The mirrors and pointers are attached to the base so all engraved lines are in a plane perpendicular to the base. A spirit level is attached to the base as shown in Figure 2.

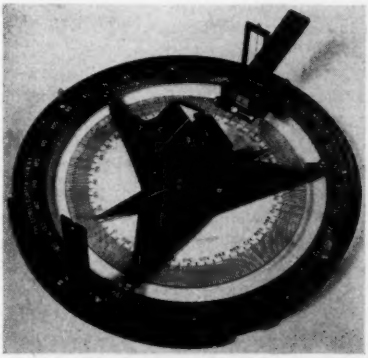


Fig. 3.—Instrument assembled and mounted on a bearing circle for installation on a gyrocompass repeater or magnetic compass.

The three pronged adapter plate is constructed to permit the reflectors, with base, pointers and dial to be placed on an azimuth or bearing circle and then set on a gyro repeater or standard 7½" magnetic compass. The stud in the center of the adapter plate, Figure 2, is in the center of the unit. The dial and reflector base are thus centered with respect to the bearing circle when assembled as in Figure 3. Adjusting screws are located in each leg of the adapter to permit the unit to be centered over a repeater or compass card even though the inner diameter of the bearing circle may not be concentric with the card.

The instrument is shown completely assembled and placed in a bearing circle in Figure 3. The bearing circle with the instrument ready for use is in Figure 5.

III PRINCIPLE OF OPERATION

Determination of direction of the earth's true north, by the conventional pelorus or bearing circle, consists of aligning an imaginary plane, passing through the sight vanes of the instrument so it is in a perpendicular plane passing through the two objects comprising the known range. When this is done, the line of sight is in a known direction, that of the range. Then to determine the true heading of the vessel, the gyro bearing of the known range is observed at the instant the vessel is on the range. The difference between the true bearing and the observed bearing by gyro is the gyro error. The error is then applied to the gyro heading and the true heading is obtained.

This instrument permits the operator to parallel a movable straight line to a known line such as that connecting two known objects, comprising a center range, as AB in Figure 1. The movable line just mentioned is a straight line through the ends of the pointers. The method of paralleling the pointers to a known center range is illustrated in Figure 4. In this Figure the observer has oriented the instrument, mounted as in Figure 5 while the vessel is approaching the range AB. He is able to see objects A and B on the reflecting elements as indicated. When the vessel moves nearer the range the observer will find it necessary to turn the instrument clockwise for the position in Figure 4 to maintain both A and B visible on the mirror hairlines. At the same time he will move his eye to a new position approaching a line vertically above the vertex of the hairlines. With the vessel on the range the observer's eye will be in a position vertically above the vertex of the hairlines. Both A and B will be visible on the hairlines at positions equidistant from the vertex at this time. The pointers are then parallel to the range. The true heading of the vessel may be determined. It has been assumed that the pointers were locked to the graduated dial on the bearing of the range.

There are certain conditions that must be maintained in order to produce accurate results. It is essential that the instrument be maintained in a level position when readings are taken at any point other than on the range. When on the range, a undirectional spirit level, such as employed on bearing circles, is satisfactory to indicate proper leveling with respect to a vertical plane passing through the range objects. It is deemed advisable for general operations to rely upon a vertical spirit level which will be satisfactory for use in both on and off the range positions. When shore lines are visible in each of the reflecting elements, the shore image in each reflector will be parallel to the vertex of the reflector and to each other if the instrument is level. If the instrument is not level, the shore line image or images will approach the vertex and base of the reflectors.

The range objects must be approximately at the same elevations when

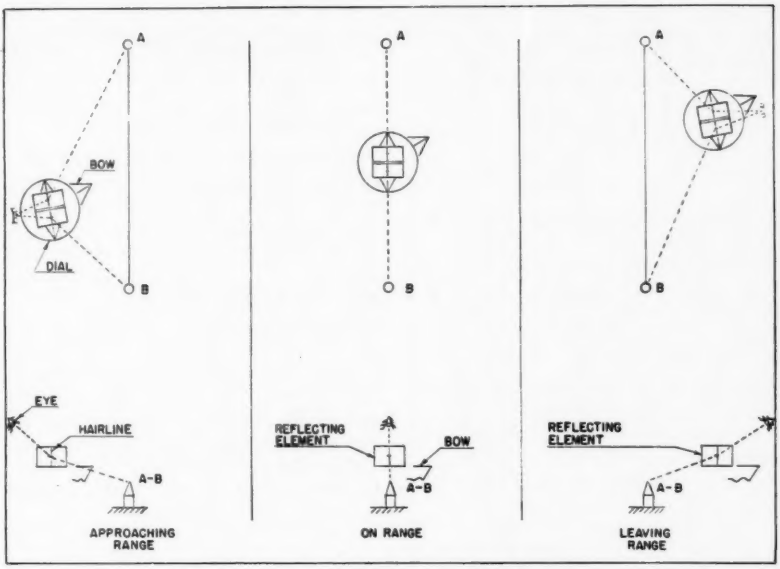


Fig. 4.—Vessel shown approaching, on and leaving a center range.

sighting from a point other than on the range. However the height of A and B, range objects may be different and introduce no error in readings when the vessel is on the range. The eye should be so positioned with respect to the instrument that images of both object A and B are equidistant from the vertex of the hairlines. When this condition is met, the eye is in a vertical plane passing through the vertex of the reflectors and at right angles to the pointers.

Errors are introduced in readings taken at positions other than on the range. The error angles may be approximated very rapidly and corrected readings taken near known positions as a vessel approaches a range. An observation taken at the position "approaching range", Figure 4, will result in the pointers set at a position, approximately as indicated. The error in the heading determined by a sight

Fig. 5.—The instrument mounted on a gyrocompass repeater.

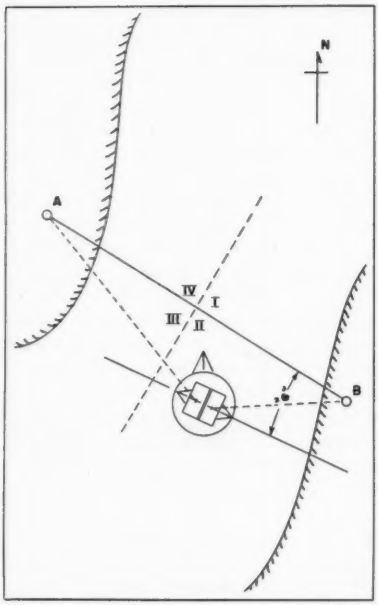


Fig. 6.—The angle "e" is the error in the reading taken at the position shown.

on the range AB, as indicated in Figure 6, is westerly because the instrument must be rotated counterclockwise to bring both A and B into view on the hairlines of the reflectors. Since the instrument is secured to the graduated dial, the 360° position on the dial is west of true north by an amount equal to "e" which is the error angle. The error for any point may be determined from a suitable hydrographic chart as follows:

1—Assume the vessel will pass abreast of point P. On the chart draw lines AB, AP, and BP, Figure 7.

2—Bisect angle APB.

3—Erect a perpendicular EL to angle bisector PH at any point.

4—Measure the angle between EL and AB. This is the error angle "e".

5—Erect the perpendicular bisector of AB. Number quadrants as shown, NE-I, SE-II, SW-III, NW-IV. The error is easterly in quadrants I and III and westerly in quadrants II and IV.

Readings taken on range AB, Figure 6, from position shown, will be in error by an amount equal to the "e". Since this reading was taken from a point in quadrant II, the error is westerly and may be corrected by subtracting "e" from the heading by instrument or by setting a "corrected" bearing of AB on dial prior to reading. If the vessel is near the range when the reading is taken, it may be preferable to apply the correction to the heading and set the correct range bearing on the dial which will permit the final readings to be taken when on the range without resetting the instrument.

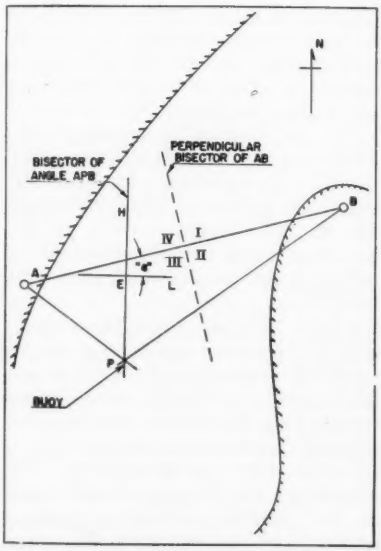


Fig. 7.—Construction of the error angle "e".

IV PROCEDURE

The actual steps in operating this instrument are outlined as follows:

1—Select the center range to be sighted and determine the range bearing from hydrographic charts.

2—Assemble for use on a gyro repeater, see Figure 3.

3—Lock pointers to the dial at the bearing of the center range.

4—Place unit on gyro repeater, Figure 5.

5—As the vessel approaches the range, observer stands in such position that the instrument is between him and range objects AB. Eyes are higher than but not directly above the instrument, see Figure 4. Adjust eye position and instrument until objects A and B are visible on mirror hairlines at points equidistant from the vertex of the hairlines. Keep instrument level.

6—Read vessel's heading by the forward lubbers line and the graduated dial as the vessel approaches range.

7—Take final reading when on range. The difference between heading by gyro and instrument is the gyro error. When the vessel is on the range, A and B are visible on the mirror hairlines which will appear to be superimposed on the white center lines of the pointers. The eye of the observer is then in a vertical plane passing through either end of the pointers, see position "on range" in Figure 4.

V ILLUSTRATIVE EXAMPLES

There are numerous situations under which this instrument may be used to advantage. Several examples are described briefly in the following paragraphs:

1—*Problem*: *Determine gyro error.* Select range and determine range bearing from chart. Bearing of range 110° true. Lock Pointers to dial at 110°. Place unit on gyro repeater, Figure 5. Take reading of heading by instrument and gyro when vessel is on the range.

Head by instrument (true)	358°
Head by gyro repeater	356°
Gyro error	2° East

2—*Problem*: *Determine deviation of magnetic compass.* Select range and determine range bearing from chart. Bearing of range 067° true. Variation 6° west. Magnetic bearing of range 073°. Lock pointers to dial 073° and place on gyro repeater stand or magnetic compass. Take readings of heading by instrument and magnetic compass when vessel is on range.

Head by instrument (magnetic)	135°
Head by magnetic compass	142°
Deviation of magnetic compass	7° West

3—*Problem*: *Determine gyro error at some known point other than on the range.* Select the range and the known point. Construct on chart the lines and angles as explained under the procedure for determining the error angle, see Figure 7. Bearing of range from chart 037°. Error angle, "e", by construction is 6° with easterly sign since point of reading is in quadrant III. The error of 6° east applied to the range bearing of 037° gives a corrected range of bearing of 043° true. Set pointers to 043°, the corrected range bearing, on the dial. Readings taken at the predetermined point are:

Head by instrument (true)	262°
Head by gyro repeater	260°
Gyro repeater error	2° East

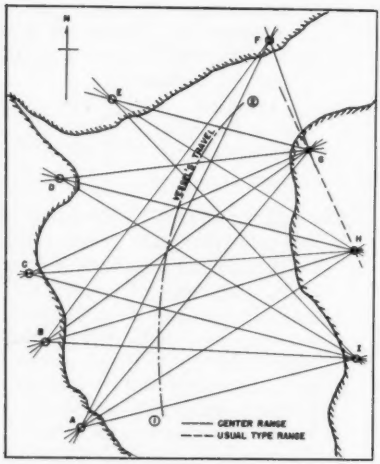


Fig. 8.—Center ranges are more numerous than usual ranges in harbor of this type.

VI CONCLUSIONS

The outstanding feature of this instrument is that it can be used on center ranges. This, in effect, increases the number of usable and visible ranges as shown in Figure 8. A vessel moving from position (1) to (2) in Figure 8 would cross some fifteen center ranges. During this travel the vessel would cross no range of the usual type.

The instrument may be placed on or removed from an azimuth or bearing circle in twenty seconds. It it constructed to permit usual sights on ranges by bearing circle while still in place as in Figures 3 and 5.

This is a practical device which has an application on surface vessels for checking gyro errors and magnetic compass deviations. It is a special instrument for a particular purpose: to determine the true heading of a vessel in a fast and accurate manner under weather conditions where visibility is such that the usual instruments and methods cannot be utilized.

VII ACKNOWLEDGMENT

The writer wishes to express his appreciation to the individuals and activities that aided in the development of this instrument: Commander Myron J. Walker, U.S.N. Retired, for his advice and encouragement; Lieutenants G. F. Kucera, H. Harms and W. German, U.S.N.R., who assisted in tests; personnel of the Optical Shop at the Norfolk Naval Shipyard for the fine workmanship in constructing the test instrument: and Lt.Cdr. A. S. Knechtel and Mr. H. F. Damron of the Magnetic Compass Section of the Bureau of Ships for assistance in the preparation of this paper.

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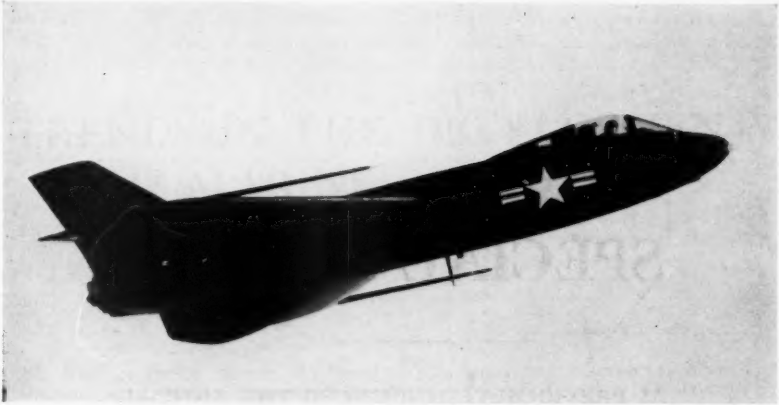


Official U.S. Navy Photograph

PART TWO

REPRINTED ARTICLES

The articles contained in this Part Two represent those which, in the opinion of the editorial staff, are the most valuable which have been gleaned from recent issues of contemporary publications.

This material was formerly published under the heading "NOTES". It has been given somewhat more prominence and made more readable to enhance its value. The editors' purpose here is to provide a convenient repository to readers of the JOURNAL, for articles originally published elsewhere which contribute to the purpose of the Society: to further the advancement of naval engineering.

SPECIAL NOTICE

AS PREVIOUSLY ANNOUNCED THE ANNUAL

BANQUET OF THE SOCIETY

WILL BE HELD AT THE STATLER HOTEL

IN WASHINGTON, D. C.

ON

FRIDAY, 28 APRIL, 1950

MR. DAVID SARNOFF

CHAIRMAN OF THE BOARD

RADIO CORPORATION OF AMERICA

WILL BE

THE PRINCIPAL SPEAKER

TRENDS IN THE DEVELOPMENT OF MARINE REDUCTION GEARING

ACKNOWLEDGMENT

This article by Mr. A. W. Davis, a member of the Institute of Marine Engineers, is reprinted from the Transactions of that Society for 1949. It deals with the advantages that can be taken in materials and design with the availability of accurate gear cutting.

Ten years ago it was generally recognized that tooth surfaces would be rough to a degree which would only provide for contact between pinion and wheel teeth on a series of unevenly distributed points, as clearly evidenced at light loading, and anyone versed in gear production at that time will recall how necessary it was that, in order to give a respectable semblance of marking on the pinion teeth, gears in the course of meshing should be revolved for a considerable period in order to ensure that each pinion tooth should engage with a large number of gear wheel teeth and thus with a large variety of gear wheel tooth profiles, and the effect produced was greatly helped in many quarters by a liberal allowance of red lead marking. The loading for which such gears were designed was based on the assumption that contact would be badly distributed and that the inertia effects resulting from bad pitch distribution would be incalculable but considerable. Papers have been presented from time to time analyzing the intensity of loading brought about by bad tooth profiles, bad helical angles, poor pitch distribution and surface irregularities and as a subject of scientific anaylsis the problems involved have indeed provided a lucrative field for theory and there is no doubt but that the tremendous improvements which have been achieved are consequent upon the interest thereby provoked. On the other hand the time has now arrived when it must be appreciated by all concerned that the scene has changed. Errors have now been reduced to a degree where it can be justifiably claimed that 80-90 per cent of the theoretical line of contact is in fact operative over the full face width, pitch errors are reduced to an insignificant value and the surface finish of the teeth has become a matter of considerable satisfaction. This is not to be complacent about the possibilities of further progress, nor is it to suggest that these attributes can be achieved without proper care and inspection, even given the necessary modern equipment of production to which reference is made in Appendices 1 and 2, but the point is that this high quality is now within the definite control of the producer and it is the business of the designer to proportion his gears in the knowledge that

such results can be achieved and of the superintendent engineers to be satisfied with no lesser standard.

Perhaps it would be appropriate to couple this last injunction with a warning that high quality gears cost more per ton weight than their less accurate predecessors, but it is to be noted that development has not overtaken economic saturation in that the reduction in size rendered possible by higher accuracy more than offsets the increased cost of production per unit weight, disregarding, of course, increases in costs of labor and material that have applied simultaneously over the period of development. On the other hand it is to be recognized that if too conservative a view is allowed to prevail in limiting tooth loading rates to figures more generally applicable to out of date gears, an uneconomical article is produced by reason of the fact that it becomes unnecessarily large for the duty expected of it.

The principal lines on which developments are now progressing and their influence on design may be treated conveniently under the following headings:—

(1) Increased loading rate to take proper advantage of accurate production.

(2) Adoption of higher duty materials as rendered possible by advent of accurately finished gears and permitting in its turn a further increase in loading rate.

(3) Improvements in tooth form permitting increase in loading rate.

(4) Effect on gear proportions introduced by the above.

The possibilities of development are also discussed in respect of the following:—

(5) Adjustment of helical angle to absorb pinion distortion.

(6) Single helical gears.

(7) Flexible couplings.

(8) Reversible gears.

INCREASED LOADING RATE TO TAKE PROPER ADVANTAGE OF ACCURATE PRODUCTION

Development in this direction is a matter of reducing what has become an exaggerated margin of safety to more reasonable limits. The difficulties of assessing such limits under seagoing conditions are numerous and well known, and their determination is bound to involve the experience of years and can only be partially assisted by experimental work on land. A typical analysis of the position is given by Appendix 3.

ADOPTION OF HIGHER DUTY MATERIALS

Development in this direction introduces both practical and economic problems.

The materials commonly employed today were generally adopted for their purpose about thirty years ago and reflect in some respects the serious difficulties which arose at that time on account of the great inaccuracy of the engaging teeth. Only materials of considerable ductility and toughness would stand up to the punishment imposed upon them without risk of failure from fatigue, although the best possible compromise was made to minimize tooth surface distress by the employment of a normalized and tempered nickel steel for the pinions with a moderately low maximum stress.

With the advent of high accuracy cutting, gears of material having a higher maximum stress and with greater surface hardness are envisaged, involving a permissible sacrifice in ductility but allowing higher surface and root stresses to be borne.

It would be represented as a failure to face the realities of the position if a certain hazard represented by the adoption of higher duty materials and heavier loadings was overlooked, in view of the inadequate experience

which has been obtained in that direction with large gears up to the present time. Clearly, the adoption of higher duty materials, in conjunction with too conservative a measure of their capacity, would lead to the production of uneconomical gear units and, perhaps, no very spectacular advance is likely to be achieved in the materials employed for merchant gears within the next few years. During this time the demand will probably be for selectively shaved gears with materials of conservative maximum stress.

In the case of naval design, the demands of minimum weight and space tend to outweigh the considerations referred to and not only materials of high maximum stress but also surface hardened and profile ground gears demand the designer's attention.

When a gear is surface hardened after cutting the teeth the distortion which occurs is inevitably such as to necessitate re-profiling the teeth and this of course can only be done by grinding. While the surface hardening of pinions is carried out in a hardening furnace under properly controlled conditions and can be a thoroughly satisfactory process, the hardening of wheel teeth, except in the case of small primary wheels, can only be carried out by a process involving a traveling flame introducing conditions which are difficult to control in insuring uniformity.

At the same time it is to be recognized that the duties which pinions perform are generally much more arduous than those of the wheels with which they mesh and that there is little to justify the case hardening of wheel teeth, since suitable heat treated steels are available wherein the hazard of flame hardening can be avoided and which can incidentally be finish processed by hobbing and shaving.

It is to be observed that gears often referred to as hardened and ground comprise pinions that are hardened and necessarily ground and wheels that are not hardened but that have been ground because grinding facilities were the only means available for accurate finishing.

Comparisons and tabular statements of the effects introduced by the employment of typical high duty steels are given in Appendix 4.

IMPROVEMENTS IN TOOTH FORM

This is a factor which has made a useful contribution to the increase in permissible tooth loading. It is fairly well established that the tip relieved involute type is the most suitable but many of the particular involute forms that have been in common use have failed to take the best advantage of the possibilities available. The matter is one of complexity but the essential features can be summarized concisely as below.

Flank Angle

Within reasonable limits the flank angle can vary without in itself affecting the suitability of the tooth. A large flank angle increases the radius of curvature of the pinion tooth and enables a greater load to be carried at the line of contact, but the effect is closely compensated for by the fact that the line of contact is itself shortened. The real importance of flank angle is to be associated with tooth depth, a small flank angle being a necessary adjunct of a deep tooth.

Tooth Depth

The greater the depth of the tooth the longer the line of contact and the greater the load that the tooth will carry from the point of view of surface stress. Considerations of gear cutting limit the depth of the teeth in relation to the pitch to about 45 per cent in excess of the British Standard tooth and for which the most suitable flank angle is about 14½ deg. Another consideration which arises is that of the ratio of sliding to rolling, which can become excessive in some circumstances when an excessively deep tooth is employed, but every satisfaction has so

far been shown by limitation in depth to about 20 per cent greater than the British Standard form, and for which the most suitable flank angle is about 16 deg. The optimum tooth forms are, in the author's opinion, always to be found between these limits and in marine reduction gearing there is no justification for so shallow a tooth as the British Standard indicates.

Pitch

The pitch of the teeth should always be the least that is permissible in relation to the root stress for the loading employed. With the materials presently employed all normal requirements for marine gears are met between the limits of 0.4 and 0.8 inch, but as suggested by the last line of Table 4, medium high tensile materials may lead to the adoption of lower pitches for small gears, while case hardened gears may necessitate the employment of greater pitches for large gears to provide a reasonable balance between surface and bending stresses, while at the same time ensuring that bending fatigue is not the criterion of failure.

Addendum distribution

The aim in assessing the distribution of addendum between pinion and wheel is to equalize the ratios of sliding to rolling at the beginning and the termination of engagement. Balance is usually sufficiently achieved by the adoption of a pinion addendum approximating to 60 per cent of the active depth of the teeth.

Helical Angle

When the cutting of gears was indifferent in quality a large helical angle was justified to reduce the shuttling action on the pinions and to increase the component of force providing acceleration for such movement. With the development of high accuracy gears, these considerations have become irrelevant and the principal objects of adopting a helical tooth become those of establishing axial location and providing against shock loading at entry to the contact zone. These requirements are adequately met by a helical angle of only a few degrees but, in view of the small increment of axial loading introduced by angles of up to 12 or 15 deg., there is little point in dropping below these limits. For this latter angle the increment of loading due to the axial component is 3½ per cent but with a helical angle of 30 deg. this rises to 13½ per cent and, accordingly, the faces of gears so designed require 10 per cent additional width. The adoption of helical angles like 40 and 45 deg. is completely unjustified today.

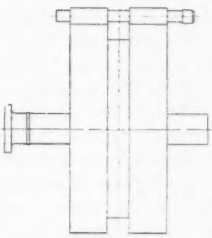
When considered in comparison with pinion diameters, the relatively narrow faced gears now commonly employed do not warrant the thinning of the ends of the pinion teeth and the requirement for a reduction of load at the ends of the teeth is adequately met by the chamfer which it is customary to provide.

EFFECT ON GEAR PROPORTIONS

It is well known that double reduction gears suffered in this country a long period of banishment because of the tooth failures which became so commonplace as a result of the gross inaccuracies introduced in their formation. With the development of accurate gear cutting the double reduction gear now takes its rightful place in the marine installation, enabling smaller turbines to be adopted with lesser risks of distortion and the use of higher pressures and temperatures without a multiplicity of turbine units.

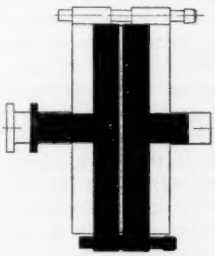
It is instructive to examine the relative sizes of a single train of gears such as illustrated in Fig. 1, where the quality of gear cutting and the loading that were standard say 20 years ago are compared with modern practice, employing similar materials. The increase in loading naturally permits a smaller gear unit, but generally the effect is not so much to reduce main wheel diameter as to introduce a reduction in the ratio of the length to the diameter of the pinions and this

GEAR AS DESIGNED AND PRODUCED IN 1928



Item		Pinion	Wheel rim
Material (see appendix 4)		H	I
p.c.d., inch		13·0	162
Face width, inch		60	
Face width/pinion p.c.d.		4·61	
Loading coefficients	$\frac{P}{D}$	575	
	$\frac{P}{De^{2/3}}$	110	

GEAR FOR TRANSMITTING SIMILAR TORQUE AS DESIGNED TO TAKE ADVANTAGE OF MODERN HIGH QUALITY FINISH



Item		Pinion	Wheel rim
Material (see appendix 4		H	I
p.c.d., inch		13·0	160
Face width, inch		40	
Face width/pinion p.c.d.		3·08	
Loading coefficients	$\frac{P}{D}$	865	
	$\frac{P}{De^{2/3}}$	165	

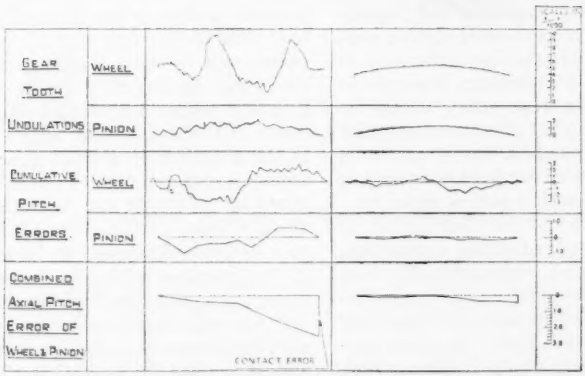


FIG. 1—*Comparative sizes and error characteristics of a single gear train of twenty years ago and today*

tends to reduce their torsional and bending deflections and minimizes the need for center bearings. The reduction of distortion leads to better distribution of load along the length of the teeth and this permits a further rise in average tooth loading; the point serves however to stress the great importance to be attached to accurate bearing alignment on relatively highly loaded gears.

ADJUSTMENT OF HELICAL ANGLE

In cases where the length of the pinion helices exceeds about 2.5 × the diameter of the pinion, consideration should be given, if reduction in the size of the gears is of paramount importance, to the introduction of a varying helical angle on the pinion teeth to compensate for distortion under load. Until recently this was a theoretical rather than a practical consideration, because of the difficulty experienced in obtaining an even marking across the face width of the gears, even under static loading conditions. To have attempted further adjustment would have been to gild a somewhat wind-blown lily and the most that could be done under the conditions that prevailed was to ensure that no heavy marking occurred at the ends of the pinion teeth.

With the availability of modern equipment for gear finishing, it is however reasonably simple, after a uniform bearing has been obtained along the teeth, to modify the helical angle of the pinion teeth by a selective shaving process so as to obtain a proper distribution under full power load. In this connection two points are to be em-

phasized—firstly, there is no advantage in attempting such adjustment on the gear before a correct static meshing has been obtained, because the errors in helical angle which cannot be dissociated from even the highest class of hobbing can be as great as the further degree of adjustment required to absorb distortion. It is therefore of no use to attempt any adjustment in the hobbing stage, even if facilities such as sine bar correctors are available on the pinion hobbing machine. Secondly, there is nothing problematical regarding the helix adjustment required and, once the manufacturing technique is mastered, to contemplate research in this field with test gears would be wholly out of place. Perhaps this point requires amplification. In the case of a pinion unadjusted for load distribution, the distortion which occurs under load and the consequent mal-distribution of load is a matter of great complexity, the calculation of which takes the form of an infinite series and is fundamentally dependent upon the flexibility of the gear teeth under dynamic conditions. The maximum loading which occurs in the case of such a gear running under load is therefore indeterminate. There is, however, no dubiety regarding the loading which exists on a gear having the pinion helices modified to provide uniform loading, the reason being that if an equal load is initially assumed to occur across the gear face, the form of pinion distortion can be calculated accurately and if the pinion teeth are finished to compensate for this distorted form an even distribution of load will be achieved effectively and the subject has no relation whatever to the unknown factors affecting load distribution on a gear not so adjusted. The subject does not therefore, in the author's opinion, lend itself to intelligent research.

SINGLE HELICAL GEARS

Something has been heard in recent years of an advantage to be found in the adoption of single helical gear units with thrust blocks to carry the out-of-balance load. This is indeed a case of the cart being put before the horse. The reason for the claim cannot be dissociated entirely from the production of ground gears, wherein the diameter of the grinding wheels is such as to require a gap of about 8 inch between adjacent helices, giving an obviously undesirable design when space and weight happen to be considerations of major importance. An aspect of this position which is not generally realized, lies in the fact that if only the pinion unit is to be profile ground on the tooth flanks, very much smaller grinding wheels may be employed because of the lesser wear which occurs in the grinding of a small gear. Consequently the gap between helices with gears of this type can be reduced to about 4 inch, enabling the advantages of a double helical gear to be retained in conjunction with the benefits of ground pinions where high loading renders the adoption of such a gear desirable. Reference to an earlier paragraph will show that the limitation of grinding to pinions is also supported by other considerations.

FLEXIBLE COUPLINGS

It is appropriate to put on record in a paper dealing with the development of marine gears that the large claw tooth sliding couplings, so widely employed until three or four years ago, are now to be regarded as out of date; their place has been taken by a small tooth coupling which can be produced with considerable accuracy and which requires a minimum of hand fitting. In operation the small tooth coupling is to be preferred, having particular regard to a number of vibrational complaints which have been attributed to couplings of the large tooth type. The members of the small tooth couplings are conveniently produced on a Fellowes type machine.

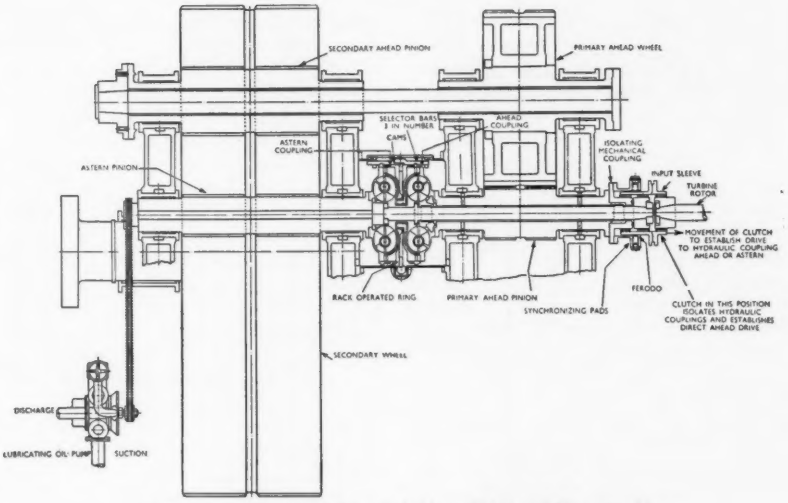


FIG. 2—*Gear with double reduction ahead drive and single reduction astern drive*

REVERSIBLE GEARS

A broad field of development has been opened up in the quest for means of obtaining reversal of propeller thrust without interruption to the normal flow of fluid in turbines. This has been necessitated primarily by gas turbine designs wherein it is not feasible to introduce an astern turbine and the matter is also one of significance in steam turbine propulsion when very high steam temperatures are employed.

The problem can, of course, be met by the adoption of propellers of the variable-pitch type but while this may have its attractions for relatively small craft, the system is unlikely to prove widely popular with owners operating larger tonnage.

The problem can also be met by electrical transmission but at the cost of at least 8 per cent loss in efficiency as compared with gearing and the introduction of complication that is not inconsiderable either in respect of initial outlay or upkeep.

Reversibility in gearing mechanism is being successfully achieved in small units by clutches of the airflex type or of the S.L.M. oil-operated type, working in conjunction with lay shaft gears. For large units two principal types are receiving consideration, both employing hydraulic reversal clutches. The first is indicated in Fig. 2, which illustrates a type of gear now being developed in which the ahead drive is double reduction and the astern drive single reduction, thereby eliminating lay shaft construction. Under astern running conditions there is a lowering of turbine revolutions and some consequent loss in efficiency but which is not incompatible with a normal astern power requirement of 70 per cent ahead power. The selection of direction of rotation is determined by which of the two hydraulic couplings associated with each turbine shaft is flooded. Under steady ahead steaming conditions a mechanical clutch is brought into operation, thereby isolating the hydraulic unit with which some 2 per cent slip is to be associated under normal conditions of driving. It will readily be appreciated that with this type of gear a relatively heavy loading is carried on the astern pinion which has its

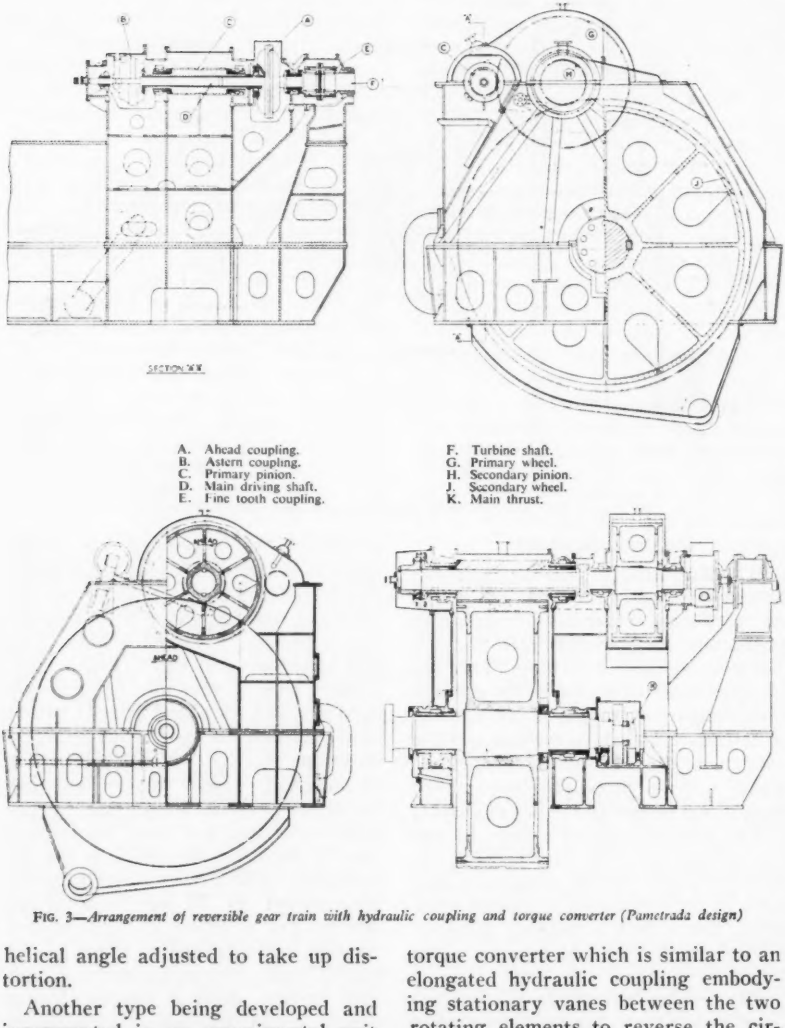


FIG. 3—*Arrangement of reversible gear train with hydraulic coupling and torque converter (Pametrada design)*

helical angle adjusted to take up distortion.

Another type being developed and incorporated in an experimental unit is referred to in a recent paper by Dr. T. W. F. Brown*. The unit is indicated on Fig. 3, ahead running being through a hydraulic coupling which is not capable of mechanical isolation and astern running through a hydraulic torque converter which is similar to an elongated hydraulic coupling embodying stationary vanes between the two rotating elements to reverse the circumferential direction of the fluid flow, this action being accompanied by a loss in efficiency of some 30 per cent, the heat equivalent of which must be carried away by the oil circulating through the coupling.

Both the above types of reversible gear are relatively straightforward in

* Brown, T. W. F. 1948. Trans. N.E.C., Vol, 65, p. 117, "British Marine Gas Turbines"

normal operation and any uncertainty existing as to their suitability rests with the ability of the couplings to dispel the heat generated when maneuvering. Experiments in this connection, with the former of the two types of gear, are being carried out and it is anticipated that valuable information will be obtained on the matter at an early date.

Before concluding the author would take the opportunity of anticipating criticism in respect of the fact that for a paper on development very little has been said of research. Is it not a word that is perhaps overstressed today? Is it not sometimes employed when what is really implied is the investigation of troubles which are known to be capable of rectification with a reasonable application of plain commonsense?

In the field of gearing development, research is certainly needed into the employment of new materials in relation to the load they will carry and their adaptability in manufacture and the matter is being pursued vigorously by Pametrada, the results being eagerly awaited by the marine engineering industry and the steelmakers.

ACKNOWLEDGMENTS

The author wishes to make acknowledgments to Messrs. William Beardmore and Co., Ltd., whose metallurgical research has enabled developments referred to in the paper to be proceeded with, and in conclusion he would thank the Directors of The Fairfield Shipbuilding and Engineering Co., Ltd. for permission to publish information given in the paper and Mr. R. P. Fullerton and members of his Design Staff for assistance in its preparation.

APPENDIX 1—EQUIPMENT FOR THE PRODUCTION OF HIGH ACCURACY MARINE REDUCTION GEARS

The principal combinations of processes in the production of large high accuracy gears are:—

(1) Hobbing and shaving.
(2) Hobbing and lapping.
(3) Hobbing and grinding.
(4) Planing and grinding.

Except where resort is made to surface hardening the most exacting requirements can be met by the first two processes listed and to which the following notes refer.

The basic requirements of hobbing machines in respect of their accuracy of motion are clearly indicated by a British Standard Specification just issued*. The specification, however, gives no guide as to whether a creep mechanism is preferable in the drive between the main worm and the master gear; the disadvantage of such a mechanism is the obvious increase in the number of working parts calling for extreme accuracy, but its advantage, particularly for large gears, lies in the fact that it renders unnecessary the supreme accuracy in the worm drive unit that it is necessary to obtain and maintain in the case of a solid table machine where error in this component produces a periodic pitch error in the cut gear, which cannot be removed by any known post hobbing process and which will introduce a whine in the finished product. In the case of a creep table machine this objection does not apply although the very greatest importance attaches to the creep ratio employed and attention is drawn to this point in Appendix 2.

The hobbing machines should be housed in temperature controlled compartments, where the variation in temperature is limited to ±1 deg. F. and a generous temperature controlled supply of cutting oil should be fed to the hobs.

A post hobbing process is most desirable to procure the finest quality of finish in the following respects:—

(1) Tooth profile, which is always liable to some inaccuracy on a hobbed gear because of the extreme difficulty of ensuring that the hob runs at all times true to its axis.

* B.S.S. 1498:1948

(2) Helical angle, the uniformity of which, between wheel and pinion, it is difficult to ensure in hobbing even under temperature controlled conditions with the best class of equipment.

(3) Surface finish, which is fundamentally below standard on a hobbed gear.

Two alternative methods of post hobbing present themselves, namely, lapping and shaving. The lapping process can be effective if it is most carefully controlled and an abundance of time is available for the process, but the danger is always present of lapping compound being left embedded in the tooth surfaces, or indeed of its finding its way into crevices of the gear units. As an economic proposition in the production of merchant gearing there is in fact little to recommend the process. The other alternative is that of shaving, which is now perfected to such a degree that it is on an economic footing for merchant as well as naval gears. The process is rapid and consists first of shaving the wheel units and subsequently shaving the pinion units selectively, i.e. by varying the infeed of the cutter so that variations of helical angle as between pinion and wheel are rectified. The process is also completely effective in correcting profile errors and in providing a polished tooth surface free from undulations, subject to the qualifications that shaving cannot be regarded as a cure for indifferent hobbing and that it is impossible to eliminate waves longer than the active width of the shaving cutter.

APPENDIX 2—CREEP FRACTIONS

The principle underlying the choice of a good creep fraction has been developed from the late Dr. Tomlinson's pioneer work on the subject and is explained in some detail on pages 256-260 of an earlier paper by the author†. It is unnecessary to repeat the underlying theory but the following essential conclusions are relevant.

The creep fraction is the decimal portion of the fraction given by the ratio wm/c where w = number of teeth in worm wheel; m = number of teeth in master wheel; c = number of teeth in creep ring. In effect the creep fraction represents the fractional difference in rotational position of the main driving worm after one complete revolution of the master wheel, the fraction representing the proportion of one revolution of the worm.

In the case of a solid drive machine the value of this fraction is zero (which may also be expressed as 0/1) and a cyclic error in the worm motion is reproduced in axial bands on the cut gear.

If a creep mechanism is introduced the value of the creep fraction should be chosen, having regard to the following features:—

(a) A creep fraction of ½ introduces the same characteristics as a solid drive but in lesser degree, because of the phasing effect of alternate feeds, and this applies in similar fashion to any other value which can be expressed as a simple fraction, the effect becoming of decreasing importance as the value of the denominator increases.

(b) A long wave undulation occurs when the creep fraction approximates closely to a simple fraction and in this connection it is important to note that the lower the denominator of the simple fraction the wider berth it should be given.

APPENDIX 3—LOADING FACTORS

The derivation of a true criterion of loading is a matter of complexity but it is nevertheless essential for purposes of design and general comparison to have a simple and reliable criterion with a knowledge of its limitations.

American practice is to employ the factor P/D_e where D_e is the pinion pitch circle diameter (p.c.d.) corrected for the finite diameter of the wheel

† Davis, A. W. 1945. Trans. I.E.S., Vol. 88, p. 179, "Current Practice in Marine Gearcutting"

with which it is meshing, by the expression

$$D_e = \frac{(\text{p.c.d.})R}{R+1} \text{ where } R = \text{gear ratio.}$$

For many years it was the practice of Messrs. Parsons Marine Steam Turbine Co. to use this expression for pinion diameters up to 10 inch and to use the expression $P/D_e^{0.5}$ for pinions above 10-inch diameter. It is known that this latter value errs on the low side in respect of the index of D_e and also that a value for this index as high as unity is not justified. When this latter value is employed the factor obtained can only be considered in relation to the size of gear referred to, that is to say, that the smaller the gear the higher the factor that may be permitted. When this consideration is overlooked, as it has been on notable occasions, the results obtained are dangerously misleading.

One authority claims than an index of 0.8 is to be desired, another that a value of ⅔ is to be preferred. A marine engine designer usually works with a slide rule having a cubic scale and the value of employing an index of ⅔ is therefore not inconsiderable as a matter of convenience and its employment is, in the author's opinion, to be encouraged, thereby giving a loading criterion of $P/D_e^{⅔}$.

The principal limitations of this factor are as follows:—

(1) There must be a limiting value of P for every tooth form in relation to the type of material employed, this being from the point of view of bending stress on the teeth, it being recognized that the factor is in itself really a function of surface stress.

(2) For purposes of comparison the factor must be regarded as a function that varies proportionally to the ratio of tooth depth to tooth pitch.

Table 1—Loading factors on gears having 45 tons per sq. in. U.T.S. pinions 35 tons per sq. in. U.T.S. rims and 30 deg. helical angle

Type of gear	Year of production	Method of finish	Loading factor $P/D_e^{2/3}$ Active tooth depth relative to British standard value $\frac{2 \times \text{pitch}}{\pi}$ $\delta = 1{\cdot}0$	$\delta = 1{\cdot}2$	$\delta = 1{\cdot}44$
Cross channel single reduction	1926	Hobbed	122		
	1936	Hobbed	128		
	1949	Selectively shaved		150	
Ocean going single reduction	1927	Hobbed	100		
	1931	Hobbed	120		
Ocean going double reduction primary	1922	Hobbed	115		
	1943	Hobbed	140*		
	1948	Selectively shaved		135	
Ocean going double reduction secondary	1922	Hobbed	85		
	1943	Hobbed			170*†
	1948	Selectively shaved			145
Destroyers single reduction					
British	1932	Hobbed	180		
British	1945	Hobbed	240		
German	1945	Hobbed	240		

* Designed abroad. † 18 deg. helical angle.

(3) If the pinion helices have not been adjusted to correct for distortion under load and the ratio of gear-face width to pinion diameter exceeds about 2.5, no center pinion bearing being fitted, then the allowable value of the loading criterion must be limited to take proper account of concentration of loading due to distortion.

Table 1 gives an indication of the limited increase that has been adopted in the loading factor over the last twenty-five years, employing wheel rims of 31/35 tons per sq. in. U.T.S. and pinions of 45 tons per sq. in. U.T.S. nickel steel, normalized or oil hardened and tempered.

APPENDIX 4—MATERIALS

Typical steels suitable for development as gear elements, together with their physical properties, are given in Table 2, in which are also included materials commonly employed today.

Table 2—Typical steels suitable for development as gear elements

Reference	Approximate analysis C	Ni	Cr	Mo	Va	Heat treatment	Process required for finishing teeth	Present usage	U.T.S., tons per sq. in.	Yield, tons per sq. in.	Elongation, per cent in 2 inch	Izod	Brinell
I	0·3	—	—	—	—	Normalized	Selective shaving	Rim-standard	35	18	26	20	150
II	0·3	3·5	0·25	—	—	Normalized and tempered	Selective shaving	Pinion-standard merchant	45	33	23	40	185
III	0·3	3·5	0·25	—	—	Oil hardened and tempered	Selective shaving	Pinion-standard naval	45	35	25	45	200
IV	0·3	3·0	0·8	0·4	0·1	Oil hardened and tempered	Selective shaving	Proposal	60	53	20	40	300
V	0·35	4·0	1·75	0·45	—	Air hardened and tempered	Selective shaving	Proposal	80	72	14	15	380
VI	0·15	3·0	0·6	—	—	Case hardened and refined	Profile grinding	Proposal	55* (root)	40* (root)	20 (root)	30 (root)	500

* There is some uncertainty as to whether these relatively high values can be obtained with large forgings

It will be appreciated that when adopting higher duty steels for increased gear loading, two principal features have to be borne in mind, namely, the resistance of the teeth to bending fatigue, which calls for a high yield strength in conjunction with a high Izod value, and the resistance to wear which calls for a high Brinell number.

Table 3 gives suitable combinations of steels for use as gear elements, together with provisional loading factors for high quality gears. Research now in progress will result in more reliable values of these factors becoming available. Relative weights and costs of units designed on the basis of these factors for transmitting the same torque as the gears referred to in Fig. 1 are given in the last four columns of the table, and Fig. 4 illustrates the resulting variation in size. To facilitate comparison relevant particulars of the gears

Table 3—Designs employing high duty steels in comparison with present standard practice

Scheme	Steels employed (see Table 2) Pinion	Rim	Remarks in respect of materials	Suggested permissible limit of loading for high quality finish with 15 deg. helix $P/De^{2.3}$ Single reduction $\delta = 1{\cdot}2$	Ocean-going double reduction Primary $\delta = 1{\cdot}2$	Ocean-going double reduction Secondary $\delta = 1{\cdot}44$	Naval $\delta = 1{\cdot}2$	Values relative to Scheme B	Suggested permissible relative maximum value of P for any one tooth form and pitch and any one class of gear	Based on single reduction gear design Relative weight of complete gear unit	Relative cost per ton Pinion and rim forgings with heat treatment	Relative cost per ton Complete gears	Relative total cost of complete gears
From Fig. 1 for reference 1928 design	II	I		(110)				(0·49)		155	95	95	147
1949 design	II	I		(165)				(0·73)		115	95	100	115
A	II	I	Standard merchant practice	200	180	200	270	0·90	1·00	110	95	100	110
B	III	I	Previously restricted to naval practice	225	200	225	300	1·00	1·00	100	100	100	100
C	IV	III	Advanced design	270	240	270	360	1·20	1·50	85	160	115	98
D	V	IV	Limit proposal avoiding profile grinding of teeth	360	320	360	480	1·60	1·50	70	190	125	87
E	VI	V	Proposal involving profile grinding of pinion teeth	450	400	450	600	2·00	1·25	60	200	140	84

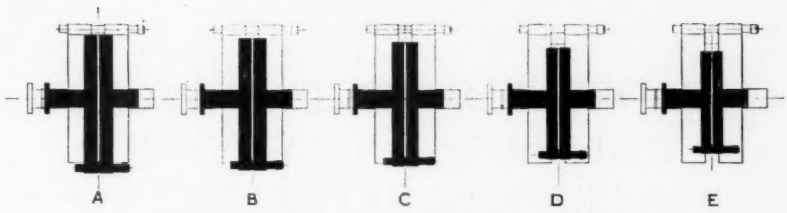


FIG. 4—*Advanced gear design compared with 1928 design for same torque*

referred to in Fig. 1 have been entered at the head of Table 3 and the outline of the 1928 design has been superimposed on each of the silhouettes appearing in Fig. 4. The comparison is further extended in Table 4 in which particulars of the gears in question are listed, the last line of the table giving an indication of tooth pitch variation as referred to in the body of the paper.

It is to be recognized that the difference between the "1949 design" and "Scheme A" represents what is today regarded as a desirable margin of safety on the suggested permissible limit.

Table 4—Comparison of gears designed for the same torque

Scheme	Repeated from Fig. 1				To limit merchant designs referred to in Table 3									
	Year 1928		Year 1949		A		B		C		D		E	
Element	Pinion	Wheel rim	Pinion	Wheel rim	Pinion	Wheel rim	Pinion	Wheel rim	Pinion	Wheel rim	Pinion	Wheel rim	Pinion	Wheel rim
Material (see Table 2)	II	I	II	I	II	I	III	I	IV	III	V	IV	VI	V
P.C.D., inch	13·0	162	13·0	162	13·0	162	12·4	154	11·6	144	10·4	130	9·55	119
Face width, inch	60		40		33		31·5		29·5		26·5		24	
Face width/pinion p.c.d.	4·61		3·08		2·54									
Loading coefficients P	575		865		1,050		1,145		1,310		1,630		1,920	
Loading coefficients $P/Dc^{2/3}$	110		165		200		225		270		360		450	
Pitch of teeth to illustrate effect of working to a uniform factor of safety in root stress as would be defined by adoption of relative maximum values of P given in Table 3, inch	0·55				0·60		0·45		0·55		0·80			

THE DEVELOPMENT OF CYCLOIDAL PROPULSION WITH PARTICULAR REFERENCE TO VOITH-SCHNEIDER

ACKNOWLEDGMENT

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INTRODUCTION

In a previous paper* the historical development of the cycloidal propeller was outlined and the system, based on the principles of the Austrian engineer Schneider, and developed by the firm of J. M. Voith, was detailed. At that time no other cycloidal system was in operation throughout the world; only 33 propellers in 20 vessels were then in service and these, apart from naval craft, operated mainly in the harbors, rivers and lakes of central Europe with a maximum of 375 h.p. per propeller. Today 250 vessels have been fitted with cycloidal propulsion and Fig. 1 shows this numerical growth for both mercantile and naval work. It also shows the increase in power absorbed: 60 per cent is of 900 h.p. or over, with a maximum of 2,200 on one propeller. The 1947 total of 550 propellers with an aggregate of 300,000 h.p., operating in 14 countries, shows conclusively that the advantages of the cycloidal propeller are appreciated.

All the above are Voith-Schneider propellers, but today cycloidal propellers are being manufactured based on

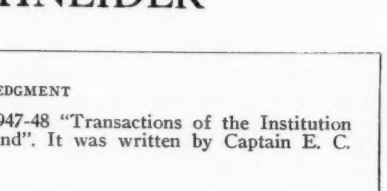


Fig. 1.

the Voith-Schneider and Kirsten systems while others are being developed on original principles.

The Kirsten propeller is a development of the Kirsten-Boeing propeller on which experiments were made in the early 1920's. The blades in the fixed-pitch type rotate on their own axis once per revolution of the propeller and are disposed in symmetrical alignment about a line passing through the center of the rotor and through the axis of the blade, which is at right-angles to the direction of thrust. Change of direction of thrust is made through a

* Trans. Inst. Eng. & Shipbldrs. in Scot., 1935-36, vol. 79, p. 97.

gear train integral with the propeller but linked to the bridge control unit through twin air motors (Fig. 2).

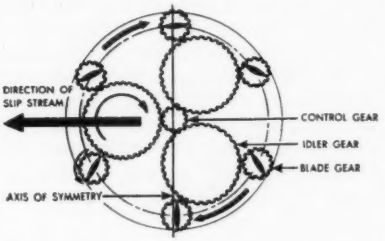


Fig. 2.

The blades of the variable-pitch Kirsten propeller perform the same oscillating motion as do those of the Voith-Schneider. The control of pitch and direction is through a mechanical gear and rack and the reciprocating action of a slidecrank—again similar to the Voith-Schneider, differing only in method of application. (Fig. 3.)

Units of both Kirsten fixed-pitch and variable-pitch propellers have been tested during the past 18 months, the former in the U. S. Navy vessel LSM.458 with two 7-ft. diam. propellers, and the latter in a 45-ft. harbor tug belonging to the U. S. Army and having two propellers each 3-ft. blade orbit diameter. Further developments are in hand, particularly on lightweight propellers for shallow-draught tugs.

VARIABLES

Two main variables associated with cycloidal propulsion are: fixed or variable-pitch; and polar or rectangular co-ordinates for steering control. It will be appreciated that with two fixed-pitch cycloidal propellers the advantages of maneuverability and lateral control can be given and that such propellers are relatively more simple than those having variable pitch. Nevertheless, variable-pitch gives the maximum advantages and, in many vessels, is justified by the improved operational efficiency.

Steering control by polar co-ordinates is analogous to the ship having screw and rudder, where a stream must be flowing past the rudder to give turning moment. With a variable-pitch cycloidal propeller and polar co-ordinates, thrust can only be given by movement of the fore-and-aft thrust control (speed lever) and the wheel when turned will then give an equal thrust the direction varying by the amount the wheel is turned. With no thrust on the propeller, that is, with the speed lever in the neutral position, no lateral thrust is given when the wheel is turned. With rectangular co-ordinates, both speed lever and wheel

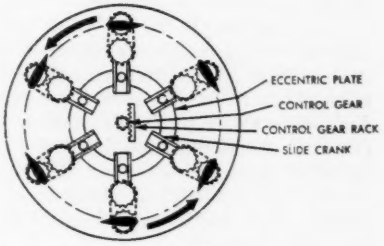


Fig. 3.

control thrust independently of each other, thus with the speed lever in the neutral position thrust would be given at right-angles to the fore-and-aft line in a degree corresponding to the amount the wheel is turned, the full power of the engines being absorbed with the wheel hard over. When steaming ahead or astern any movement of the wheel produces an angular change of thrust which is the resultant of the amounts of movement from the neutral position of both speed lever and wheel. All variable-pitch cycloidal propellers can rotate without giving thrust, but with rectangular co-ordinates both speed steering controls must be in the neutral position, whereas with polar co-ordinates the speed lever only need be neutral.

SHIP TYPES

Shallow Draught. About 90 per cent of the vessels fitted with cycloidal propellers have a draught of 6 ft. or less and it would appear, both from theoretical considerations and practical results, that this method of propulsion should always be considered for shallow-draught vessels. The large swept area and low speed of revolution ensure good propulsive efficiency which, coupled with the variable pitch and maneuvering characteristics, substantially improve the serviceability of these craft, and particularly so for towing vessels, as the results of the past 12 years on the Niger, Rhine, Danube and other rivers have shown. Many tropical rivers at certain seasons bring down massed agglomerations of weed and undergrowth, sometimes so dense as to support animals and effectively bar the passage of paddle and screw ships. The *Katsena* on the Niger has demonstrated that the horizontal rotation of the cycloidal propeller can cut through dense "sudd," though it closes up so quickly that paddle vessels directly astern are stopped.

The weight of a cycloidal installation compares favorably with screw and rudder since reverse gear, thrust block, tail shaft and screw, shaft brackets, rudder and stock are eliminated. Nevertheless, for very shallow-draught vessels or for special types a lighter weight may be required, as with the 250-h.p. tug built for Army Engineers for transport by road. The main casings of the Voith-Schneider propeller consisted of 5 per cent magnesium-aluminium alloy castings, while other parts were cast in 10 per cent silicon-aluminium alloy, replacing the fabricated mild steel structures and bronze castings and giving a saving of some 50 per cent in the total weight. The materials stood up well to service conditions, and further developments of the light-weight propeller for special ships may be expected.

A feature appreciated in light-scantling shallow-draught passenger ships is the absence of vibration with the cycloidal propeller. This is presumably because any part of the blade is a constant distance from the hull and thus works in the same water velocity, whereas the tips of a screw are under changing velocity conditions with every revolution. This feature may also be of benefit to naval vessels wishing to avoid detection from sound recording apparatus.

Ferries.—Of the mercantile vessels fitted with cycloidal propulsion, ferries predominate. They vary from the small harbor ferry-cum-tug of under 100 h.p. to the miniature cross-channel ship typified by the *Helgoland,* a turbo-electric vessel of 4,000 h.p. on two shafts. Two such vessels operating in this country are the *Lymington* on the former Southern Railway service Lymington-Isle of Wight, and the *Abercraig* belonging to the Dundee Harbor Trust on the Dundee-Newport service. Maneuverability is of prime importance, as is also good propulsive efficiency, especially where speed materially affects the time of transit. An appreciation of the service requirements, the length of voyage, the hydrographic conditions and approach to terminal ports will determine the position for the propellers to give optimum results in service. Table I gives tank test results of a vehicular and passenger ferry of 630 tons displacement with two sizes of propellers each being tested in three different positions.

The results show the improved hydraulic efficiency with increased swept area. They show also the low efficiency of a bow propeller, unavoidable whether it be cycloidal or screw: the adverse effect the slipstream has on the after propeller and the reduction of this latter influence by staggering. The service on which the vessel operates is 2½ miles between terminal ports. The loading is a straight-through

TABLE I

Dimensions:
167 ft. o.a. × 38 ft. mld. × 5 ft. 1 in. draught.

Constants:
Ship's speed—11 knots.
Displacement—630 tons.
Two propellers 6 blades each—

A { 1,600 mm. orbit diam.
  { 1,000 mm. blade length.

B { 2,000 mm. orbit diam.
  { 1,100 mm. blade length.

		Propellers fore and aft in line	Propellers fore and aft staggered	Propellers at stern
A	B.h.p.	1,240	985	698
	η hydr.	28.2	35.4	49.3
B	B.h.p.	1,085	860	620
	η hydr.	32.4	40.6	56.3

STOPPING TESTS

Ship's speed 10¾ knots.
2 Propellers, size A, at stern.

Shaft h.p. -	392	638	712	848
R.p.m. - -	113	130	138	146
Distance for stopping (ft.)	350	295	280	250
Time for stopping (sec.)	42	34	32	31

drive for the vehicles, thus calling for a double-ended vessel unless two turns of 180° are made every other passage. With two stern propellers this vessel turns 180° in less than 30 sec., so that despite the turns a speedier passage on the same power is given than with a double-ender. The greater efficiency and higher speed is also available when on long trip charter work, and for these reasons stern propellers were fitted.

Further tank tests were made on this model to determine the effect of the divergence of the propeller streams on the hydraulic efficiency. The results showed that with two stern propellers 4 per cent less power was required when the streams were 5° outwards than when parallel. This, no doubt, is due to less interference of the two

Fig. 4.

jets, which was demonstrated when the vessel was completed and on trials. Fig. 4 shows the stern wake with slightly converging streams, while Fig. 5 shows the stern wake with diverging streams of approximately 5°. With increased divergence over 5° tank tests showed that any advantage would gradually decrease, as would be expected since the forward motion would be the resultant of the two streams. The optimum angle of divergence can be readily found in service, and fixed by a simple adjustment of the control levers.

Fig. 5.

The excellent stopping power of the cycloidal propeller is demonstrated by the fully loaded vessel being brought to rest from full speed in about half a minute and in 1¾ lengths. Good stopping power is essential to vessels operating in congested waters and this example is no exception where at one of the terminal ports is a narrow entrance and short quay length with a current of 4 knots at spring tides across the face, thus demanding good speed of entry. Tank tests on this vessel but with screw propulsion showed that the stopping power with screws was not sufficient for operational safety.

With short-passage and heavily-loaded straight-through vehicular or train-carrying ships, the propulsive efficiency may be of less importance than optimum lateral control, in which case the propellers should be situated one at either corner as with the train ferries across the Danube.

Floating Cranes. The advent of the cycloidal propeller was welcomed by the operators of floating cranes and a number have been fitted, varying from the Japanese 30-ton crane with two propellers at the stern driven by 75 h.p. electric motors, to the 350-ton floating cranes, the largest in the world, with dimensions 205 × 108 ft. and 5,000 tons displacement which have three 750-h.p. propellers (two at the stern and one in the middle line forward). An interesting conversion in 1937 was the pontoon of a dumb crane for Gothenburg which was suitably modified and fitted with two propellers, one on either side of the midships section through-coupled to one Diesel engine of 240 h.p. placed athwartships.

Floating cranes demand good maneuverability and propellers must be positioned to give maximum control with the most efficient propulsion. In all cases it is desirable to move bodily sideways and this can be achieved with two propellers at the stern as shown

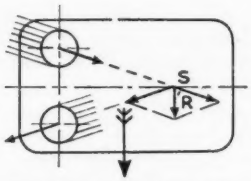


Fig. 6.—Athwartships thrust with two propellers aft.

in Fig. 6. The magnitude of the athwartships thrust, apart from considerations of power employed, will vary with the distance between the two propellers, so that full advantage should be taken of the beam. With only two propellers the maximum athwartships thrust can be given by placing them one at each end of the vessel but at opposite corners, in order to give the best propulsive efficiency (Fig. 7). In larger cranes—and in fact

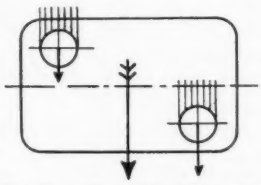


Fig. 7.—Athwartship thrust with fore and aft propellers.

others where there is ample electric power—there should be three propellers, two at the stern and one in the center line forward (Fig. 8). With this arrangement optimum efficiency is given for propulsion and lateral thrust. Other craft such as dredgers having similar characteristics to floating cranes are also improved with cycloidal propulsion.

Fire Floats. Cycloidal propulsion is the only practical method of keeping fire floats in position when subject to reaction from the jet. The vessels can also be designed with a shallower draught but with an equally good propulsive efficiency to lie nearer to the

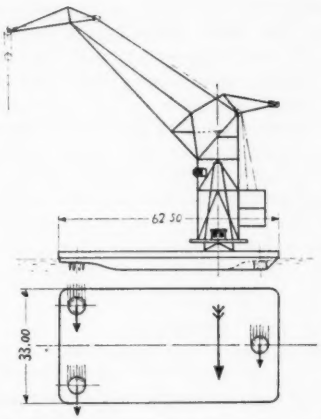


Fig. 8.—Athwartships thrust two propellers aft, one forward.

seat of the fire. This is of some importance in tidal rivers or harbors which dry out some distance from the shore. The machinery is simplified, since the propulsion engine can drive the pumps and, by varying the pitch, as much or as little of the power can be absorbed on one or the other. The successful operation since 1937 of the Paris fire floats has resulted in similar orders being placed throughout the world.

Large Ships. Though the cycloidal propeller is not, to date, advocated for the propulsion of large ocean-going ships, it may claim serious consideration as the steering unit. Its superior efficiency at low speeds would minimize danger of collision or stranding when in fog or navigating narrow channels. Furthermore, vessels could with safety enter or leave port under conditions which would stop the movement of normal rudder-controlled ships. Foerster* showed that in a 30,000-ton displacement passenger ship having twin screws of 45,000 s.h.p. total, a Voith-Schneider propeller with the same steering effect as a corresponding balanced rudder at the full speed of 25 knots was also capable of propelling the ship without the screws at 10 knots. At this speed the steering effect of the cycloidal propeller was three times that of the rudder (Fig. 9).

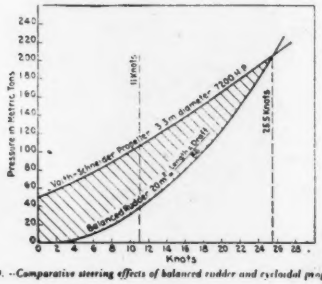


Fig. 9.—Comparative steering effects of balanced rudder and cycloidal propeller.

The following are three examples of the application of cycloidal propellers as steering units:

The cable ship *Toyo Maru* is fitted with screws and rudder for normal movement, but has in addition a Voith-Schneider propeller driven by a 100-h.p. electric motor for use when the ship is handling cable. This allows her to work under conditions which would effectively stop operations were she fitted only with screws and rudder (Fig. 10).

The German aircraft carrier *Graf Zeppelin* had two Voith-Schneider propellers for control at low speed and when navigating narrow channels and in passage through the Kiel and other canals. They were situated in the fore-and-aft line well forward, each driven by 450 h.p. electric motors and housed in separate closed compartments. These propellers can also be raised inside the ship to give a clean hull line when steaming in open waters.

A cycloidal propeller has been fitted as the auxiliary steering unit in a submarine, placed forward in a narrow compartment open to the sea, with the blades horizontal. The propeller was designed and tank-tested for a 600-ton boat but was eventually fitted in one of 900 tons and, although the desired

* Trans. Soc. Nav. Arch. & Mar. Engr., 1936, vol. 44, p. 228.

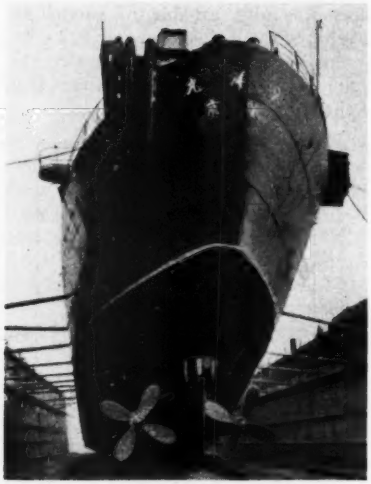


Fig. 10.

thrust of 2,200 lb. was obtained, it was insufficient for the larger displacement boat. Nevertheless, the results proved its efficacy for this purpose.

For cross-channel passenger and train ferries requiring to turn and move astern in restricted waters the addition of a forward cycloidal propeller would appear to be a logical safety measure. It would also give freedom of operation even in the worst weather.

DESIGN DEVELOPMENTS

No fundamental change in construction has taken place with the Voith-Schneider propeller since 1933, but development work now in hand may lead to simplification and higher hydraulic efficiency. Certain detail improvements have been effected as the result of practical experience, such as the use of chrome steel runner wheel bottoms to avoid corrosion in ships operating in salt water. The carbon packing in the stuffing box and the leather cups on the blade shafts have been changed to Buna rings. The former gave trouble through grease, sand and carbon deposits jamming the action of the spring, thereby destroying the seal and leading to heavy wear on the rotating face. The Buna rings in the stuffing box are cooled by water from the runner wheel pump vanes. Buna cups on the blade shafts have reduced wear and give a more efficient seal since, being a synthetic product, they have a constant quality, unlike leather which is dependent on the hide of the animal and the variables in manufacture. Other minor modifications have been made for simplicity of construction and erection.

RELIABILITY

The results of the past 15 years with the cycloidal Voith-Schneider propeller have shown that generally, where annual overhauls are given, no major upkeep charges occur, but as with all machinery, much depends upon the knowledge of and attention given to the propeller in service and at overhauls. With any fundamental development in ships a breakdown is a matter of comment, suggesting that the human element has not changed since the days of Brutus! Out of more than 250 ships fitted—and some operated by unskilled native labor—the writer is aware of only one installation that has been removed and replaced with another form of propulsion. This was in no way due to the failure of the Voith-Schneider propellers, which had operated continuously and without overhaul for 3 years, during which time only one minor part was renewed, and on dismantling examination showed that, apart from the normal wear which would be expected on plain bearing surfaces, all internal parts were in excellent condition and capable of giving many more years of service.

It may well be claimed then that practice has justified theory and that the cycloidal propeller is comparable in reliability with other marine installations, is unrivalled for certain classes of ship and is established as a method of propulsion as surely as was the paddle and still is the screw.

LARGE-SCALE TORSIONAL FATIGUE TESTING OF MARINE SHAFTING

ACKNOWLEDGMENT

This article by Mr. S. F. Dorey, Chief Engineer Surveyer, Lloyds Register of Shipping, describes the design and construction of a new large type of torsional fatigue testing machine, as well as certain tests carried out on large diameter shafts. It is reprinted from the "Proceedings of the Institute of Mechanical Engineers" for 1948.

Introduction. It has been known for many years that when a material is tested under fluctuating stress conditions the size of the test piece may have some effect on the endurance limit. In general, however, comparisons have been made, in the case of torsional tests, between specimens varying in diameter from 0.25 inch to 2 inches. The results of a few tests relating to specimens 3 inches in diameter have been published, but above this size extremely limited information is available. This is mainly due to the cost involved in building a machine, together with the cost of the specimens and, in respect of alternating torsional fatigue testing machines, the amount of power necessary to drive the machines. The latter difficulty can, however, be overcome by designing a machine so that the specimen can be stressed by making it serve as the spring member in a mass-elastic system and vibrating it torsionally at or near the natural frequency of the system. The machine described in this paper was designed by employing this principle and using a special design of torque exciter to induce the alternating torsional stress in the specimen.

It might be well to refer to the reasons leading up to the demand for a large-scale alternating torsion testing machine.

Stresses causing failure of large mild-steel marine shafts appear to be appreciably less than those obtained when employing test specimens of diameter of about 0.3 to 0.5 inch and allowing for the effect of stress raisers (e. g. fillets, keyways, lubricating holes, and notches)*. In the majority of cases, shaft failure was known to be caused by excessive torsional vibration stresses, and a knowledge of the true fatigue strength of large forged shafts was required for the assessment of the vibration stresses (arising during both transient and continuous operation) which permitted a reasonable life of shafting. In addition, a knowledge of the reduction of fatigue strength due to fillet radii, oil holes, keyways, and knifing of coupling bolt holes was necessary.

Impetus for this large-scale fatigue testing, in this country, was given during the war by the Admiralty, and

* DOREY, S. F. 1938-9 Trans. North East Coast Inst. Eng. and Shipbuilders, vol. 55, "Strength of Marine Engine Shafting".

arose through a proposal to use thick solid-drawn steel tubes—approximately 10 inches diameter and 6 inches bore, with flanges welded on—in place of forged shafts. Before adopting this type of shafting, however, it was considered desirable that fatigue tests should be carried out on full-sized specimens.

At about this time, a new type of torsional vibration damper and torque exciter had been designed and patented by Dr. G. H. Forsyth, while he was in charge of engineering research at Lloyd's Register of Shipping. The first of its kind had been made (by Messrs. W. H. Allen, Sons and Company, Ltd., Bedford, to the order of Messrs. The Wellman Bibby Company) for dealing with an exceptionally severe shaft critical in an oil-engined vessel. The ship in question, however, was sunk before the damper could be fitted and the latter was used as a torque exciter in the construction of a large torsional fatigue testing machine. The torque exciter for the initial experiments was loaned by Mr. J. Bibby, from whom it was ultimately acquired.

The Exciter. Fig. 1 shows details of the torsional vibration exciter. It will be observed that this consists of two plates bolted rigidly together, forming a cage. Between the two plates are mounted three pairs of meshed out-of-balance wheels, one wheel in each pair being rigidly connected to a planet pinion meshing in turn with a sun-wheel mounted on the outside of the cage (Fig. 2). The three pairs of planets are arranged symmetrically in the cage at intervals of 120 deg., and by suitable phasing all the six meshed, out-of-balance wheels develop maximum torque at the same instant (Fig. 3); moreover, the radial components of the centrifugal forces are in balance at all times. For the exciter used in the testing machine, the maximum forcing torque is given by

$$T = 0.0146N^2 \text{ lb.-in.} \quad . \quad . \quad . \quad . \quad (1)$$

at N r.p.m. of the planet pinions, the Wr per planet being 8.37 lb.-in., and the orbital radius of each planet being 10¼ inches.

It should be understood that the torque exciter in the machine under

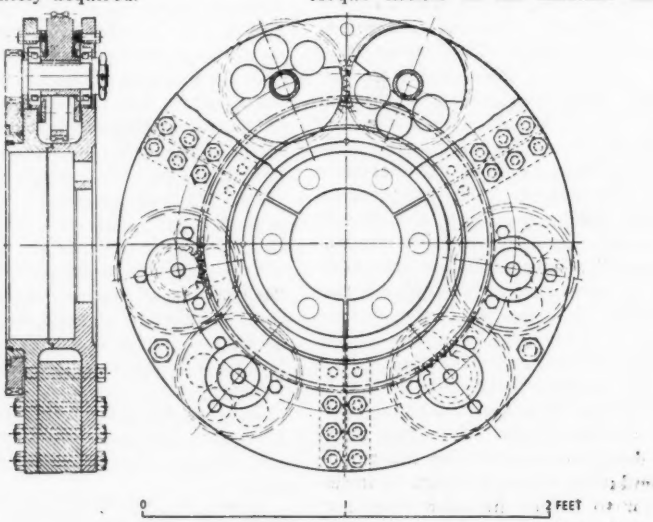


Fig. 1. Torsional Vibration Exciter

Fig. 2.—Torsional Vibration Exciter.

notice is applied to a stationary shaft. It can, however, equally well be applied to a rotating shaft, and the principle involved is indicated in the Appendix.

The Torsional Fatigue Testing Machine. Fig. 4 and Fig. 5, show the arrangement adopted for testing mild-steel shafts. The test piece forms a short bobbin shaft mounted in a central pedestal bearing, the test portions being of 9¾ inches, outside, and 6¼ inches, inside, diameter. After some

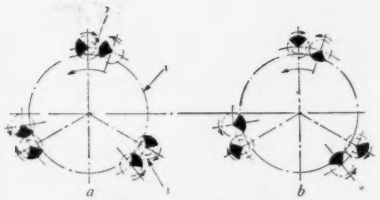


Fig. 3. Phasing of the Out-of-Balance Wheels
a Maximum torque. *b* Zero torque.
1. Sun-wheel.
2. Planet pinion.
3. Out-of-balance planet-wheels.

consideration, a length of about 2 feet between flanges was decided upon, having regard to economy of space and weight of test piece. The calculated torsional stiffness of the shaft is 350×10^6 lb.-in. per radian twist.

In order to eliminate the transmission of vibration to the foundations of the machine, a two-mass torsional system has been adopted by bolting a heavy cast-iron flywheel to each of the flanges of the test shaft, and the machine is run as closely as necessary to the resonant frequency of the system, the exciter cage being rigidly attached to one of the flywheels, and a counter balance weight equal to that of the exciter bolted to the other flywheel.

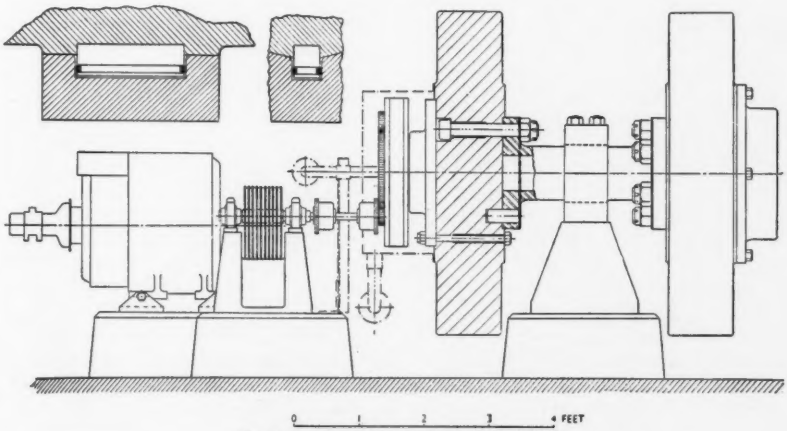


Fig. 4. Arrangement for Testing Mild-Steel Shafts

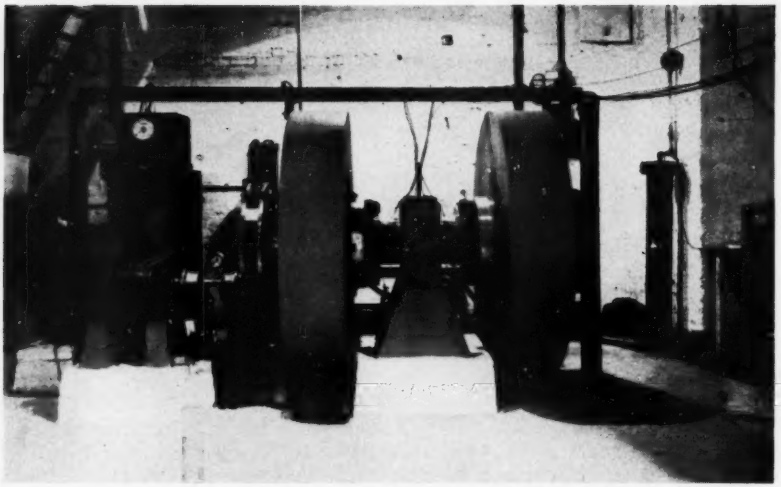


Fig. 5.—Arrangement for Testing Mild-Steel Shafts.

The actual flywheels fitted are 5 feet in diameter by 12 inches thick, and weigh approximately 4 tons each.

Fig. 2, shows the drive to one of the pinion shafts, and the latter, by rotating the sun-wheel, drives the remaining pinions. The drive embodies a cardan shaft with flexible couplings at either end. With this arrangement the pinion can vibrate freely torsionally about its own axis, and laterally as a result of the torsional displacement of the test specimens. The remaining part of the drive is through a nine-strand Tex rope from a 30-h.p. shunt-wound D.C. motor. The shaft speeds of the planet pinions and of the motor are 2,500 r.p.m. (nominal) and 1,200 r.p.m. (nominal) respectively.

The mass-elastic system formed by the two flywheels and the test shaft was designed for a natural frequency of about 2,500 vibrations per minute. The test shaft is supported at the nodal point corresponding to resonance. Difficulty was envisaged with the pedestal bearing, on account of frettage corrosion and from excessive vibration transmitted to the foundations before resonance was reached. Further, vibratory energy had to be transmitted through this bearing to the flywheel remote from the exciter. Accordingly, for the initial tests the key in the central journal was provided with a measure of torsional flexibility by means of a rubber ring arranged in a groove, the keyway in the cast-iron pedestal bearing being given adequate clearance. Further, frettage corrosion has been largely eliminated by arranging rubber sealing rings in circumferential grooves at each end of the pedestal bearing, the bearing clearances being pumped solid with zinc oxide grease.

The latest practice, however has been to use a solid key, bearing on a flat milled in the shaft journal; that arrangement has proved entirely satisfactory with no appreciable vibration of the pedestal bearing. It should be mentioned that the bearing is very slightly tapered on the lower half on both sides from the center, leaving an effective bearing length of about 3 inches in order to minimize damping.

The calculated natural frequency F_n of the two-mass torsional system is

2,450 vibrations per minute, the effective moment of inertia at each flywheel being 10,600 lb.-in.-sec.^{2} units. The amplitude of the harmonic vibration torque T_v in the shaft at any forcing frequency N vibrations per minute, assuming the system to be undamped, can be shown to be

$$T_v = \pm \frac{0.0073N^2}{1-\left(\frac{N}{F_n}\right)^2} \quad . \quad . \quad (2)$$

and the amplitude of vibration stress f_v in the test shaft is given by

$$f_v = \pm T_v/Z \quad . \quad . \quad . \quad . \quad (3)$$

where Z is polar sectional modulus of shaft in inch-cubed units. By substitution, it follows that

$$f_v = \pm 48.1 \times \frac{\left(\frac{N}{1{,}000}\right)^2}{1-\left(\frac{N}{F_n}\right)^2} \quad . \quad . \quad (4)$$

Fig. 6 shows the theoretical undamped resonance curve plotted to a base of vibrations per minute. Also plotted on the same diagram is the actual measured resonance curve for No. 1 test shaft having a butt welded flange at one end and a fillet welded flange at the other. The measured value of natural frequency is 2,420 vibrations per minute and this value has been used for F_n in plotting the theoretical curve from equation (4). The forcing stress in the shaft at 2,420 vibrations per minute is $\pm 96.2 \times (2.42)^2 = \pm 564$ lb. per sq. in.

The measured vibration stress at resonance was found to be $\pm$ 16,800 lb. per sq. in.

Thus, dynamic magnifier at resonance is

$$\frac{16{,}800}{564} \text{ or } 30.$$

In the case of the latest specimen tested, a solid forged shaft of 28-32 tons quality, it was found possible, with the shaft cold, to reach a stress of about $\pm$ 20,000 lb. per sq. in., the resonant frequency having increased to

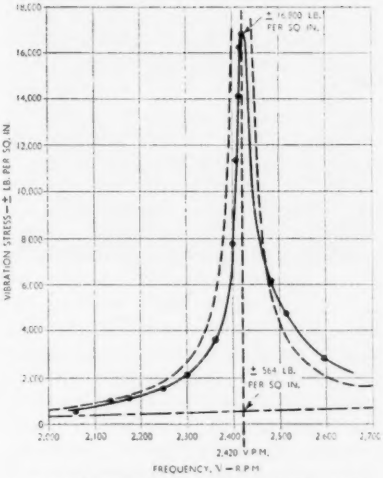


Fig. 6. Resonance Curve for Mild-Steel Welded Shaft of 9¼ 6½-inch diameter

—●— Measured results from shaft No. 1.
— — — Theoretical undamped resonance curve.
— · — Stress due to forcing torque.

2,620 vibrations per minute on account of the greater shaft stiffness of the solid specimen.

The calculated static bending stresses in the 9¾-inch diameter shaft due to the deadweight of exciter and flywheel are low, being only 2,600 lb. per sq. in. at the edge of the pedestal bearing journal and 1,660 lb. per sq. in. at the commencement of the flange fillet, a further argument for a short length of test piece. These small steady bending stresses would have negligible influence on the torsional fatigue strength of the shafts.

In the earlier experiments, with a view to protecting the machine from damage in the event of sudden failure, or excessive amplitude of vibration after the initiation of fatigue cracks, two limit switches were fitted at the perimeter of each flywheel, one on the horizontal diameter to control tangential movement and one at the top of the vertical diameter to safeguard against bending deflection. The Burgess micro-switches were all wired in series,

and operated a relay to open the motor starter switch when the displacement at any one switch exceeded the pre-set value.

From an examination of the resonance curve for the machine, the importance of accurate speed control is self-evident from the steepness of the curve. Initially, no automatic speed control was fitted to the machine, the regulation of speed being effected by a hand-operated rheostat in series with the motor shunt field winding. In carrying out tests on the 9¾-inch diameter shafts described in this paper the inertia in the machine enabled steady conditions to be obtained in conjunction with this hand control, even on the steep portions of the resonance curve. With rigid supervision it was possible to maintain the stress steady within ± 5 per cent of the nominal value in way of the steep portion of the resonance curve.

With a view to reducing the amount of supervision necessary with manual control, an automatic electronic system of control has been developed which has also reduced the variation of stress at the maximum loading to ± 1 per cent.

The system of operation is, briefly, as follows:—

(*a*) To minimize the effect of wide line voltage fluctuations experienced with the works D.C. supply, a motor-generator set was installed to operate off the A.C. supply.

(*b*) The field of the motor driving the harmonic torque exciter is controlled directly by a battery of thermionic power valves operating in parallel. The conductance of these valves is made to vary over a very wide range by means of grid control provided by a control valve.

(*c*) The control signal to the grid of the control valve is obtained as follows:—

(1) A small multi-polar permanent magnet alternator is solidly coupled to the driving motor shaft (see (*b*) above).

(2) The signal from this alternator (approximately 300 cycles per second) is amplified and rectified to provide approximately 230 volts D.C.

(3) A stabilized D.C. voltage of 230 volts is provided as a datum.

(4) The driving motor line voltage together with the rectified 300 cycles per second signal are, in correct sense, backed off against the above stabilized datum voltage.

(5) The difference signal is then used to swing the grid of the control valve, the grid bias of which is chosen for optimum performance.

This system of control, which has been recently developed by Mr. T. W. Bunyan, is an improvement on that adopted in most of the tests, has been in use in the latest tests (1947), and has functioned very satisfactorily.

Stress Measurements. At all times during the running of the tests the actual strain in the test shaft was directly indicated by means of electric resistance strain gauges, the stress being derived from measurements of the wave amplitude on the cathode-ray oscillograph. The gauges were affixed to the shaft as shown in Fig. 7, i.e. several gauge pairs on either side of the center bearing, the straining axes of the gauges being at 45 deg. to the shaft axis. It is considered unnecessary to include any further details in this paper concerning the now well-established technique of strain measurement.

The design described has been found entirely satisfactory so far as the

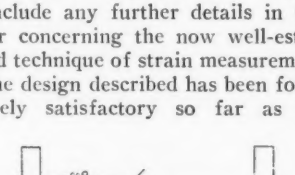


Fig. 7. Positioning of Gauges on the Test Shaft

operation of the machine is concerned. It was found, however, that the bolted arrangement of test piece to flywheels was expensive and, a demand being made for testing cast-iron shafts of 6 inches diameter, a simplified arrangement was designed. In consequence the form of the test piece has been changed to that shown in Fig. 8 and the flywheels have been replaced by testing heads as shown in Fig. 9. Fig. 10, shows the modified machine being used to test a cast-iron shaft.

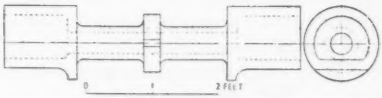


Fig. 8. Modified Form of Test Piece

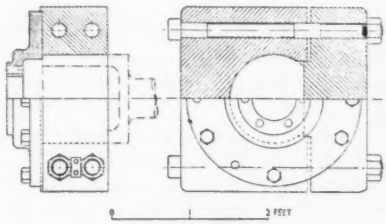


Fig. 9. Testing Heads

The modified design is simple so far as the machine is concerned; it has proved entirely satisfactory in operation, and will be used for future tests.

Tests on Shafts with Welded-on Flanges. Altogether four tests were carried out on welded shafts, three test pieces being used, test shaft No. 2 being formed from test shaft No. 1—by cutting off the flange where failure took place in the butt weld, and welding on another flange. The fillet weld in test No. 2 had therefore been previously subjected to the cycles of stress applied during test No. 1.

The tube material of the shaft and flanges was of 26-32 tons per sq. in. quality, and the joints were made by metallic arc welding in accordance with Admiralty Grade A requirements.

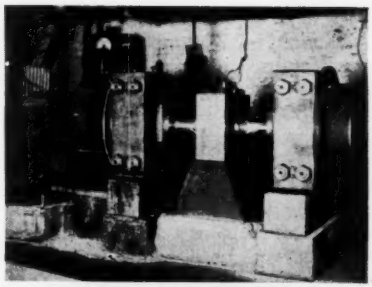


Fig. 10.—Modified Machine Testing Cast-Iron Shaft.

The welded shafts were stress-relieved at a temperature of 600-650 deg. C. and radiographic inspection was carried out by X-ray from outside the shaft, using special screens, and from inside by gamma ray, using radon. Shaft No. 5 was not radiographed because the porosity in the welds was obvious to the naked eye. After final machining and before fatigue testing the shafts were magnetically tested.

The surface finish was in each case ordinary smooth-turned finish, but without any polishing process. The weld preparations for the various test shafts are indicated in Fig. 11. In the case of test shaft No. 1, the butt joint was welded with an oxy-acetylene base run followed by arc welding with ¼-inch diameter Lincoln "Fleetweld" No. 6 type electrodes. Similar technique was used with the fillet weld.

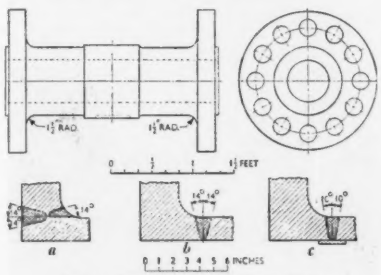


Fig. 11. Weld Preparations for Test Shafts

Test shaft No. 1: Fillet *a*, Butt *b*.
Test shaft No. 2: Fillet *a*, Butt *c*.
Test shaft No. 4: Butt *c*, Butt *c*.
Test shaft No. 5: Fillet *a*, Fillet *a*.

In welding on the new flange for test shaft No. 2, a mild-steel backing ring was used and the runs were deposited by arc welding throughout in the downhand position, the shaft being slowly rotated during the welding operation. Preheating at 400 deg. F. was used for test shaft No. 4 which had both flanges butt welded. In the first run of welding a ⅜-inch diameter electrode was used, while in the remaining runs (thirteen in number) ¼-inch diameter electrodes were employed, all electrodes being "Fleetweld".

The welding areas were also preheated to 400 deg. F. before welding in the case of test shaft No. 5, and slightly different techniques, with "Fleetweld" electrodes, were employed for welding the two flanges.

Fig. 12, indicates the fatigue cracks initiated in test shaft No. 4, while Fig. 13, illustrates those in the case of test shaft No. 5, showing the porosity in the weld.

The fatigue test results for these test shafts are given in Table 1.

These results indicate that, unless very special care is taken in the welding operation, couplings welded to shafts may have a comparatively low fatigue strength when subjected to alternating torsional stresses. This may be largely due to lack of homogeneity of the material in the weld area, with resulting increased susceptibility to fatigue failure.

Tests on Solid Forged Shafts. In view of the low fatigue strength obtained for the welded shafts, the Admiralty decided to have tests carried out on forged shafts, and three in all were tested for them. The material employed for test shaft No. 3 had a tenacity of about 35 tons per sq. in., and in the case of the other two forged shafts, 28-32 tons per sq. in. The forged test shafts were identical with the welded shafts as regards dimensions, with the exception that the fillet radii in the case of test shafts Nos. 6 and 7 were approximately 2 instead of 1½ inches.

The test results for the forged shafts are given in Table 2. In view of the results obtained for specimens Nos. 6 and 7, the author decided to carry out an additional test, on shaft No. 8, with a view to ensuring that fracture would

Fig. 12.—Fatigue Cracks in Test Shaft No. 4.

TABLE 1. WELDED TEST SHAFTS

Test shaft No.	Ultimate tensile strength of shaft material, tons per sq. in.	Ratio: Shaft diameter / Fillet radius	Torsional stress, lb. per sq. in.	No. of cycles	Remarks
1 F.B.	26–32	6·5	± 5,000 ±16,000 ±13,200	2×10^6 96×10^3 72×10^3	Trial run on machine. Initiation of fatigue cracks in butt weld from which 45 deg. cracks occurred locally.
2 F.B.	26–32	6·5	± 7,000 ±10,000 ±12,500	$9·5\times10^6$ 8×10^5	Fatigue cracks in fillet weld. Test abandoned.
4 B.B.	26–32	6·5	± 7,500	$7·2\times10^6$	Cracks developed in one butt weld (Fig. 12, Plate 2).
5 F.F.	26–32	6·5	± 6,500	4×10^6	Cracks developed in both welds (porosity) (Fig. 13, Plate 2).

F.B. One flange fillet welded, one flange butt welded.
B.B. Both flanges butt welded.
F.F. Both flanges fillet welded but slightly different technique used for each.

take place initially in the coupling fillet and not in the keyway. For this purpose a shaft was forged to represent an intermediate shaft of normal merchant service design, the shaft being solid, with coupling fillet radii of one-eighth the diameter of the shaft, viz. 1-7/32 inches. In this test specimen a solid key was fitted to a flat milled on the shaft journal, as already described.

Fig. 14, indicates the fatigue crack which originated in the fillet of test shaft No. 3. Material was taken from this shaft and tested on a torsional fatigue testing machine at the National Physical Laboratory, using specimens of 0.5 inch diameter. The torsional fatigue limit so determined was $\pm$ 10 tons per sq. in.

In the case of test shaft No. 6, it will be observed that a different technique was carried out. Large-scale fatigue tests are very expensive and the question arises as to whether it is really necessary to use the same technique as hitherto used for small specimens. In the latter case, about six specimens may be used to determine the curve of number of stress cycles to rupture, and, from this curve, the fatigue limit. For small specimens of steel it has been found that, provided the fatigue stress is just low enough to permit the specimen to withstand 10^7 cycles of stress, a very great number of cycles of this stress can be endured. To reduce, from six to one, the number of test pieces required in large-scale testing, it was planned to commence testing at a low fatigue stress and after each 10^7 cycles to increase the stress in small increments until failure occurred. This procedure was also adopted for test shafts Nos. 7 and 8.

Automatic control of stress, to replace manual control, was also applied for tests Nos. 6, 7, and 8. Figs. 15 and 16 illustrate the cracks formed at the

Fig. 13.—Fatigue Cracks in Test Shaft No. 5.

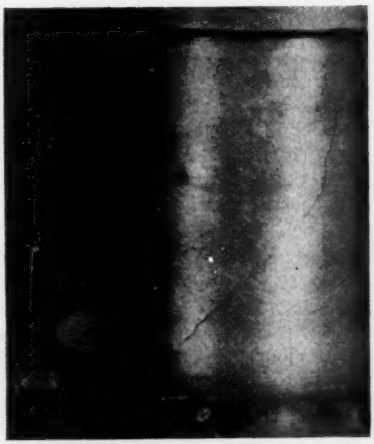


Fig. 14.—Fatigue Crack in Test Shaft No. 3.

Fig. 15. Cracks in Hollow Forged Test Shaft, No. 6
28–32 tons per sq. in.

Fig. 16. Cracks in Hollow Forged Test Shaft, No. 7
28–32 tons per sq. in.

keyway for these former two specimens, respectively. The diameter of specimens in way of the keyway was 10½ inches, so that the nominal stress was, for all tests, approximately 70 per cent of that on the section of 9¾ inches diameter.

When test shaft No. 6 had been subjected to 5×10^6 cycles at a stress of ± 13,500 lb. per sq. in., the top half of the bearing was removed, and, after a thorough cleaning the whole surface, including keyways and fillets, was inspected for cracks under a magnifying glass; no sign of failure could be detected. After 7×10^6 cycles at ± 15,000 lb. per sq. in., it was noted that a fall in frequency had occurred. The first visible sign of fracture was noticed after 396,000 cycles at ± 16,500 lb. per sq. in. in the fillet adjoining the enlarged portion of the shaft forming the center bearing. The top half bearing was then lifted and three cracks were noted, as indicated in Fig. 15.

Test No. 7 was carried out under somewhat similar conditions to test No. 6. From the experience obtained in the previous test it was anticipated that fracture of the shaft would occur in the keyway. In consequence, the top half of the bearing was removed after 10^7 cycles of stress had been completed at ± 13,500 lb. per sq. in., and again after 6.51×10^6 cycles at ± 15,000 lb. per sq. in. Careful inspection did not reveal the presence of cracks. The temperature of the shaft was 85 deg. F. until 7×10^6 cycles of stress had been completed at ± 13,500 lb. per sq. in., when it rose rapidly to 200 deg. F. No further notable increase in temperature occurred until 6.9×10^6 cycles had been completed at a stress of ± 15,000 lb. per sq. in., when a temperature of 320 deg. F. was attained. The shaft remained at this temperature until failure after 8.09×10^6 cycles at ± 15,000 lb. per sq. in. A fall in frequency was not noted until 8×10^6 cycles of stress had been run at ± 15,000 lb. per sq. in.

As shown in Table 2, the solid forged

TABLE 2. FORGED SHAFTS

Test shaft No.	Ultimate tensile strength of shaft material, tons per sq. in.	Ratio: Shaft diameter / Fillet radius	Torsional stress, lb. per sq. in.	No. of cycles	Remarks
3	35	6·5	±10,000	$7{\cdot}2 \times 10^6$	Crack formation commenced at slight tool mark in fillet (Fig. 14, Plate 2).
6	30·5	5 approx.	± 7,500 ± 9,000 ±10,500 ±12,000 ±13,500 ±15,000 ±16,500	1×10^7 „ „ „ „ „ $3{\cdot}96 \times 10^6$	Cracks originated in the keyway at the nodal point of the shaft (Fig. 15).
7	33	4·875	±10,500 ±12,000 ±13,500 ±15,000	1×10^7 „ „ $8{\cdot}09 \times 10^6$	Cracks originated in the keyway at the nodal point of the shaft (Fig. 16).
8	30·5	8	±10,000 ±11,500 ±13,000 ±14,500 ±16,000 ±17,500	1×10^7 „ „ „ „ $8{\cdot}1 \times 10^6$	Cracks originated in the coupling fillet (Fig. 17, Plate 2).

test shaft No. 8 failed after 8.1×10^6 cycles at $\pm$ 17,500 lb. per sq. in., after having previously withstood 10 million cycles at each of five lower stress ranges commencing with $\pm$ 10,000 lb. per sq. in. Fig. 17, shows the appearance and location of the fracture in the coupling fillet adjacent to the exciter. It is interesting to record that when the stress was increased from $\pm$ 16,000 lb. per sq. in. to $\pm$ 17,500 lb. per sq. in. the shaft surface temperature rose rapidly from approximately 195 deg. F. to 282 deg. F. This was accompanied by a reduction in the maximum stress on resonance of from $\pm$ 20,000 lb. per sq. in. for the cold shaft to $\pm$ 16,500 lb. per sq. in. for the hot shaft. Cooling air from a fan was then applied to the shaft; the air reduced the surface temperature to approximately 200 deg. F. The maximum stress obtainable on resonance at this temperature was of the order of $\pm$ 18,000 lb. per sq. in. The test was run off at this temperature and the stress of $\pm$ 17,500 lb. per sq. in. was steadily maintained until failure occurred. Shaft surface temperatures were measured by means of thermo-couples and also by temperature-sensitive wire resistance strain gauges applied to the shaft. Fig. 18 indicates the temperature variation in relation to the number of cycles, also to vibratory stress, from which it will be noted that a very rapid rise of temperature occurs during the application of the final stress of $\pm$ 17,500 lb. per sq. in. Owing to the high temperatures reached during this final run, it was found desirable to supplement the strain gauges measuring shaft stress by an electro-magnetic type of vibration pick-up measuring the tangential oscillation of one of the flywheels at a convenient radius. This pick-up had previously been calibrated while the shaft was cold, in terms of stress indicated by the strain gauges on the shaft.

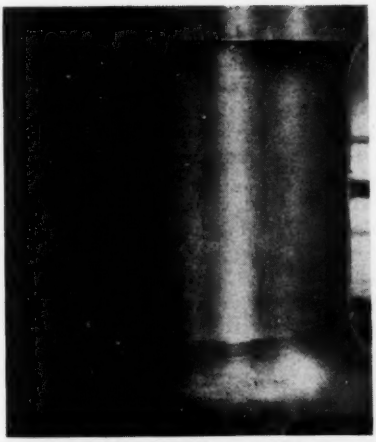


Fig. 17.—Fatigue Crack in Solid Forged Test Shaft No. 8.

Small, polished test pieces, ½ inch in diameter, cut from the forged material of this shaft and tested in reversed torsion on the National Physical Laboratory's combined-stress machine, gave a fatigue limit of approximately $\pm$ 9 tons per sq. in., giving a value of about 1.17 for the overall factor, $\triangle = f/F$, where f represents the reversed torsional fatigue limit of a ½-inch diameter, polished specimen without stress concentration, and F represents the reversed torsional fatigue limit of a 9¾-inch diameter solid test shaft with stress concentration due to a fillet radius of one-eighth shaft diameter and with commercial, smooth-turned finish, the fatigue strength being

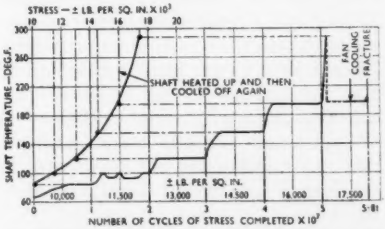


Fig. 18. The Relation of Shaft Temperature (by thermo-couple) and Stress, or Number of Cycles of Stress Completed, for Test Shaft No. 8

estimated from the results of the special testing procedure adopted.

The results obtained with test shafts Nos. 6 and 7 would seem to show a value for $\triangle$ of about 2 for a sunk keyway with rounded ends.

German Large-scale Torsional Fatigue Testing Results. For comparison with the results of the fatigue tests described in this paper, it may be of interest to mention the results of somewhat similar large-scale torsional fatigue tests carried out in Germany during the war for the German Admiralty*.

The tests were carried out on separate similar crank throws having a pin diameter of 9.65 inches, the crankpin forming the spring member of a two-mass torsional vibration system, and being clamped by its webs to two equal oscillating masses with its pin co-axial with that of the machine. This arrangement was shown by Lehr and Ruef* to approximate most nearly to actual service conditions, having regard to normal clearances usual in main bearings. Centrifugal forces provided the excitation, a pure reversed torsional couple being applied to one of the oscillating masses at a testing speed of the order of 1,000 vibrations per minute. The dimensions of the crank webs were unfortunately not given, but an idea of the design may be derived from the perspective sketch in Fig. 19. The crankpin was hollow bored about 50 per cent on diameter with a fillet radius of 0.59 inch. The corresponding ratio of pin diameter/fillet radius (about 16½) represents normal crankshaft practice. It will be noted that the crankwebs were heavily chamfered, and only about 40 per cent of the crankpin diameter in axial thickness.

The crank sections were forgings made to specification St.C.35,61, which requires a tenacity of 35-41 tons per sq. in.

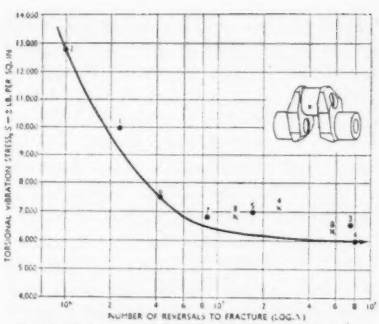


Fig. 19. Endurance Curve for Forged-Steel Crank Throws (German Tests)

Crankpin 9·65 inches in diameter.

× Stress values artificially raised by previous fatigue testing at lower stresses.

Altogether eight throws were tested and Fig. 19 shows the endurance curve obtained. The results for the various throws are numbered from 1 to 8. The endurance curve was drawn through the lower limit of the "scatter" region and shows a limiting fatigue stress of ± 6,000 lb. per sq. in. It is important to note that the number of cycles given in this diagram is the number actually required to fracture the shaft, and not the number to produce the first detectable fatigue crack. For example, in the case of crank No. 3 the first fatigue crack occurred after 7 million cycles, but the final fracture did not take place until after 75 million cycles. With the exception of cranks Nos. 4 and 7, all fatigue cracks commenced in the fillets.

An interesting point brought out by this series of tests was that the fatigue strength seemed to be almost unaffected by the presence in the pin and fillet surfaces of numerous small flaws only capable of resolution under the "Magnaflux" process, the theory being that such flaws mostly do not represent actual cracks, but are small groups of the finest slag inclusions. The effect of flaws in the form of cracks large enough to be visible to the naked eye was not investigated, however.

To obtain some idea of size effect, a smooth test piece of St.C.35,61 of dia-

* Lehr, E., and Ruef, F. 1943 *Motortechnische Zeitschrift*, vol. 5, p. 249.

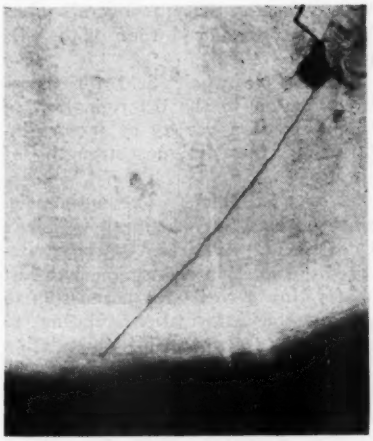


Fig. 20.—Fatigue Crack in Test Shaft A of Cast Mechanite.

Fig. 21.—Fatigue Crack in Test Shaft C of Cast Mechanite.

meter 1.18 inches gave a reversed torsional fatigue limit of about ± 23,000 lb. per sq. in., which is in good agreement with National Physical Laboratory results already quoted for test shaft No. 3. This comparatively high value must, of course, be attributed in some measure to the negligible stress concentration produced in a standard smooth test piece of this size. In considering the results given in Fig. 19, it should be remembered that the ratio d/r for the fillet was 16.5 as compared with 6.5 for the author's test shaft No. 3, and it is considered that the difference in d/r values could account to some extent for the different fatigue results obtained. A value of about 3.8 is indicated for the overall factor $\triangle$, based on a diameter of 1.18 inches for the small test piece.

Tests on "Meehanite" Cast-Iron Shafts. It has been previously mentioned that certain alterations were made in the large fatigue testing machine in order to test a number of cast-iron shafts, and as the shafts in question were 6 inches in diameter, it is considered it would be of interest to include the results in this paper. The shafts in question were of cast Meehanite and, through the courtesy of Mr. R. B. Templeton of the Ealing Park Foundry, the test results are shown in Table 3. Figs. 20 and 21, indicate the crack development for test shafts A and C respectively.

Small-scale torsional fatigue specimens, ½-inch diameter, gave a value of

TABLE 3. MEEHANITE CAST-IRON SHAFTS

Test shaft	Ultimate tensile strength of shaft material, tons per sq. in.	Ratio: Shaft diameter / Fillet radius	Torsional stress, lb. per sq. in.	No. of cycles	Remarks
A	30	6·0	±4,080 ±5,190 ±6,300 ±7,420 ±8,530	1×10^7 " " " $8{\cdot}15\times10^6$	Crack developed in shaft material, and spread in 45 deg. spiral into the fillet (Fig. 20, Plate 2).
B	30·5	6·0	±8,500	$8{\cdot}16\times10^5$	Grain structure of shaft material coarser than shaft A. Several cracks developing.
C	31	6·0	±7,000 ±8,000	1×10^7 $3{\cdot}65\times10^6$	Crack developed very rapidly (15 minutes), starting from fillet and proceeding as 45 deg. helix (Fig. 21, Plate 2).

± 7.7 tons per sq. in. for this material. It had been previously ascertained that reversed bending tests had indicated a fatigue limit of approximately ± 12 tons per sq. in.

It is difficult to assess with confidence a value for scale effect, but in these tests a value of about 2 is indicated for the overall factor $\triangle$.

General Conclusions. The results so far obtained with this large torsional fatigue testing machine indicate clearly the overall reduction in fatigue strength in large shafts due to stress concentration set up by the geometrical form of the stressed parts, to lack of homogeneity of the material, and to any size effect, if present.

So far as size effect is concerned, the results obtained for mild-steel test shafts Nos. 6, 7, and 8, tested in the manner described in this paper, show that the effect may be very appreciably less than that given by other investigators when comparing test results over a considerably smaller range of diameters.

In the case of Meehanite cast iron, the limited evidence provided by the tests indicates that the overall effect is more pronounced than with mild steel.

There is a whole field for future investigation in the determination of the effect of a variety of factors influencing the fatigue strength of shafting.

Acknowledgments. The author desires to thank the Engineer-in-Chief's Department, Admiralty — who sponsored the work in connection with test shafts Nos. 1 to 7—for permission to publish the information relating to these tests; to express his appreciation of the assistance rendered by Mr. T. W. Bunyan, Mr. S. Archer, and other members of the Chief Engineer Surveyor's Research Staff at Lloyd's Register of Shipping, in carrying out the tests; also to record his indebtedness for the valuable services rendered by Messrs. The Staveley Coal and Iron Company in providing the site and facilities for the tests; and, finally, to acknowledge the part played by Dr. G. H. Forsyth, through whose ingenuity and zeal the experiments were made possible.

Appendix.

Theory of the Torque Exciter as Applied to the Generation of a Harmonic Torque upon a Uniformly Rotating Shaft.

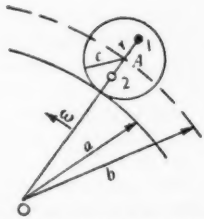


Fig. 22. Single Planet in Limiting Radial Positions (1) and (2)

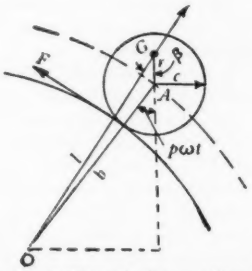


Fig. 23. Single Planet in Intermediate Position

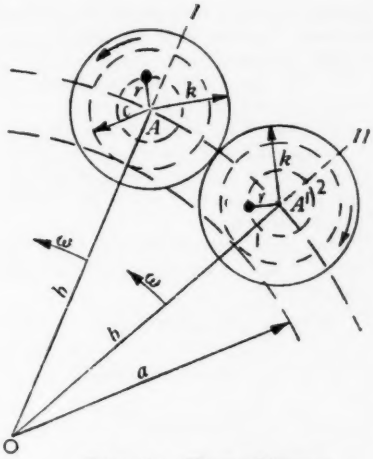


Fig. 24. Twin Planets

Energy Method. (*a*) *The Effect of a Single Planet.* In relation to Figs. 22–24, let

W = weight of out-of-balance planet-wheel (lb.).

r = eccentricity of center of gravity of planet-wheel about its own axis of rotation A (inches).

b = orbital radius of planet-wheel about axis O (inches).

a = pitch radius of fixed sun gear (inches).

c = pitch radius of planet pinion (inches).

p = gear ratio = a/c.

ω = angular velocity of cage carrying planet-wheels, assumed uniform (radians per second).

T_h = maximum value of harmonic torque on exciter cage (lb.-in.).

F_h = maximum value of harmonic torque reaction on fixed sun gear (lb.).

Angular velocity of planet pinion relative to radius arm OA rotating at ω radians per second

$$= a/c \times \omega = p\omega$$

Absolute angular velocity of planet pinion in space

$$= (p + 1)\omega$$

Since ω is assumed to be uniform and the sun gear is fixed, there will be no angular acceleration of cage or planet-wheel. Thus, only changes in the instantaneous values of the kinetic energy of the planet-wheel, as determined by the absolute velocity in space of its mass center, need be considered.

The kinetic energy of the planet-wheel in position (1) as shown, with its mass center in the extreme outward position is given by

$$E_1 = [(b + r)\omega + pr\omega]^2W/2g$$

and in the extreme inward position (2) by

$$E_2 = [(b - r)\omega - pr\omega]^2W/2g$$

and change in kinetic energy from position (1) to position (2) is

$$E_1 - E_2 = [\omega^2br(p + 1)]2W/g \quad . \quad (5)$$

Corresponding to this reduction in kinetic energy, an equal amount of external work must be done against the

harmonic torque exerted by the exciter in order that the cage velocity ω may remain constant.

Let the magnitude of this harmonic torque after time t be given by $T = T_h \sin p\omega t$. The angle turned through by the cage about its axis O, while planet-wheel turns π radians about its axis, A, from position (1) to position (2) is given by π/p radians.

Work done against harmonic exciting torque T while cage turns through the angle π/p is

$$U = \int_0^{\pi/p} T \cdot d(\omega t)$$

$$= \int_0^{\pi/p} T_h \sin p\omega t \cdot d(\omega t)$$

$$= -\frac{T_h}{p}\left[\cos p(\omega t)\right]_0^{\pi/p}$$

$$= \frac{2T_h}{p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Equating (5) and (6):—

$$\frac{2T_h}{p} = [\omega^2 br(p+1)]2W/g$$

$$T_h = [\omega^2 br(p^2+p)]W/g \quad . \quad . \quad (7)$$

At any position of the planet pinion, other than the extreme radial limits (1) and (2), there must clearly be a harmonic torque reaction, $F = F_h \sin p\omega t$, acting on the sun gear due to the moment about the planet axis (A) of the centrifugal force exerted on the out-of-balance planet mass, W/g, caused by the uniform general rotation ω about the exciter axis, O (Fig. 23).

At any instant (t), let the radial distance of the mass center G, of the out-of-balance planet-wheel from the exciter axis O, be l, and let the angle OGA between l and r be denoted by β.

The centrifugal force acting at G, radially outward from O, due to general rotation (ω), is $(\omega^2 l)W/g$. The moment (T_A) of this force about planet axis A is $[\omega^2 lr \sin \beta]W/g$ and as $l \sin \beta = b \sin p\omega t$:—

$$T_A = [\omega^2 rb \sin p\omega t]W/g \quad . \quad . \quad . \quad (8)$$

Taking moments of external forces about planet axis A:—

$$F_c = [\omega^2 rb \sin p\omega t]W/g$$

i.e.

$$F = [\omega^2 rb/c \sin p\omega t]W/g.$$

Moreover $b/c = p + 1$.

Therefore

$$F = [\omega^2 r(p+1) \sin p\omega t]W/g$$

and the maximum value of F occurs when $p\omega t = \pi/2$, i.e. when the planet radius GA, is at right angles to the cage radius OA, and is of magnitude

$$F_h = [\omega^2 r(p+1)]W/g \quad . \quad . \quad . \quad (9)$$

(*b*) *The Effect of Twin Planets.* It has been seen that with the single-planet type of exciter a harmonic torque reaction will be imposed on the stationary sun gear due to the general rotation ω, and this reaction reverses in sign at each of the extreme positions (1) and (2), setting up hammer and noise in the gearing.

With a view to relieving the sun gear of this reversal of tooth load, the twin-planet type of exciter was conceived, in which a second out-of-balance planet-wheel II of equal weight W, eccentricity r, and orbital radius b is carried in bearings in the exciter cage and arranged to be driven by 1/1 gearing from the first planet-wheel I, as shown in Fig. 24.

Following the same method as used for the single-planet type, let E_1' and E_2' be the kinetic energies of the out-of-balance planet-wheel II in the extreme positions (1) and (2), respectively, which are arranged to be 180 deg. out-of-phase with the corresponding positions of planet-wheel I:—

Then $E_1' = [(b - r)\omega + pr\omega]^2 W/2g$

$E_2' = [(b + r)\omega - pr\omega]^2 W/2g,$

and

$$E_1' - E_2' = \omega^2 br(p-1)2W/g \quad (10)$$

Again, in a similar way, it may be shown that the external work done against the harmonic torque $T' = T_h' \sin p\omega t$ during the change from position (1) to position (2), in order that the general speed of rotation ω shall remain uniform, is given by

$$U' = \frac{2T_h'}{p} \quad . \quad . \quad . \quad . \quad (11)$$

and, equating (10) and (11),

$$T_h' = [\omega^2 br(p^2 - p)]W/g \quad . \quad . \quad (12)$$

By addition of the harmonic exciting torques for the two planets, the resultant amplitude of harmonic cage torque for a twin-planet unit is obtained:—

$$T_{h2} = (\omega^2 brp^2)2W/g \quad . \quad . \quad . \quad (13)$$

Similarly, the harmonic torque set up about the axis A′ of the planet II due to the general rotation ω can be shown to be given by

$$T_A' = (\omega^2 rb \sin p\omega t)W/g$$

which is equal to that set up about the axis A of planet I, but is clearly of opposite sense. Thus the two torques are always balanced at the point of meshing (Q) of the 1/1 gears, with the result that the sun gear is completely relieved of all tooth loading other than the steady frictional driving load.

The Method of Lagrange. Dr. G. R. Goldsborough, using the method of Lagrange for the mathematical analysis, obtained the same results.

ELECTRONICS—PAST, PRESENT AND FUTURE

ACKNOWLEDGMENT

This article is reprinted from the "Journal of the Franklin Institute" for November 1949. It is by Mr. W. C. White, of the General Electric Research Laboratory, Schenectady, New York.

The science of electronics is usually thought of as being new, but this is hardly the case. This year, the "Journal" is celebrating its 123rd year and, of course, this antedates all except the most elemental observations in this science. However, quite a little had been done as long as 50 years ago.

In 1898 the word "electron" had been in print for seven years. The British scientist, J. J. Thomson, had made the first evaluation of the charge on the electron and Thomas A. Edison had received a patent (fourteen years earlier) on the use of a hot-cathode, two-electrode tube for use as a voltage regulator in the Edison central station system that he was developing.

In another branch of what today is considered electronics, a German physicist had established pretty thoroughly the fundamentals of the mercury-arc rectifier as we know it today. In still other branches of the science, the use of alkali metals for sensitive phototubes had been discovered and the cathode-ray oscillograph had been disclosed with its deflection of beams by electric and magnetic fields.

Of course, this is the familiar pattern of most technical developments. The fundamental research and the disclosure resulting from it precede by several years the practical application. An attempt has been made to show this in the charts that accompany this article. For this purpose the field has been divided into six classifications and the fundamental discoveries basic to each part of the field are listed in connection with a time scale. Included also are the development and practical utilization of the basic ideas that were later evolved.

It is of interest to consider further this matter of the time that elapses between the conclusion of a piece of basic research and when the product is generally available.

Radio High-Vacuum Tubes

Fundamental Research	Approximate Year of Publication	Approximate Year of Availability	Development
Loss of electric charge from hot metals (du Fay)	1725		
Year given is for date of publication or announcement	1800		The selected research results at the left laid the foundation for the products listed below with approximate year commercially available.
	1850		
Hot electrodes lose + and − charges at different rates (Guthrie) Conduction in vacuum from a hot cathode (Edison Effect) Word "electron" coined for indivisible unit of electricity (Stoney) Evaluation of charge of electron (J. J. Thomson)			
	1900		
Basic work on thermionic emission of electron (Richardson) Secondary electron emission (Austin and Stark) Electron emission from oxide-coated cathodes (Wehnelt) The grid electrode for control (de Forest)			The Fleming valve wireless detector The de Forest audion
Ductile tungsten (Coolidge) Pure electron discharge in high vacuum (Langmuir and Arnold)	1910		
Diffusion pump for high vacuum (Gaede) High-vacuum condensation pump (Langmuir) Use of getters in electron tubes Additional grid for high amplification (Schottky) Electron emission from thoriated tungsten (Langmuir)	1920		High-vacuum and high-power diodes and triodes Broadcast triode transmitting and receiving tubes
A-c heater cathode (Freeman) Metal-to-glass seal for large diameter cylinders (Housekeeper)			
			Screen-grid transmitting tubes Rectifier tubes for a-c receivers A-c operated receiving tubes Screen-grid receiving tube Magnetron (multi-anode oscillator)
Screen-grid for radio-frequency amplification (Hull and Williams) Demonstration of wave nature of electrons (Davisson and Germer) Secondary emission suppressor grid (Holst and Tellegan) Early work on electron microscope (Ruska and Rudenberg) Strain free alloy seals (Scott and Hull) Steel-envelope technique	1930		Pentode

		Steel-envelope receiving tube
		Beam power tubes
		Klystron
	1940	
		Disk-seal triodes

Use of Electron or Ion Beams in High Vacuum

Fundamental Research	Approximate Year of Publication or Availability	Development
Fluorescence from ion bombardment (Plucker)	1859	
	1860	
	1870	
Beam of electrons in high vacuum and its deflection by magnetic and electric fields (Crookes)		
	1880	
	1890	
Use of ion beam for oscillography (Braun)		
	1900	
Electron emission from oxide-coated cathodes (Wehnelt)		
The grid electrode for control (de Forest)		
	1910	
Pure electron discharge in high vacuum (Langmuir and Arnold)		
		Coolidge high-vacuum X-ray tube
Wave motion theory of electrons (de Broglie)	1920	
	1930	
		General use of cathode-ray tube for oscillography
Early work on electron microscope (Ruska and Rudenberg)		
		Cathode-ray tube for television reception
		Iconoscope camera tube for television
		Cyclotron (custom built only)
		Beam power tubes
		The Orthicon
	1940	One-million-volt industrial X-ray equipments.
		Electron microscope
		20-million-volt induction accelerator
		100-million-volt induction accelerator
		Mass spectrometer
		Electron diffraction instrument
		Phasitron tube for FM transmitters
		Image Orthicon camera tube for television
		Cathode-ray projection tube for television

Tubes Sensitive to Light—Phototubes

Phasitron tube for FM transmitters
Image Orthicon camera tube for television
Cathode-ray projection tube for television

Tubes Sensitive to Light—Phototubes

Fundamental Research	Approximate Year of Publication / Availability	Development
Photo-emission of electrons from alkali metals (Elster and Geitel)	1890	
	1900	
Secondary electron emission (Austin and Stack) Basic Theory of photoelectric effect (Einstein)		Phototubes available (custom built)
	1920	Sensitive material on an interior electrode Phototubes commonly available at low cost
	1930	
Secondary electron multipliers	1940	
		Multiplier phototube

Cold-Cathode Discharge Tubes

Fundamental Research	Approximate Year of Publication / Availability	Development
Research on glow discharge in gases (Faraday)	1838	
Fluorescence from ion bombardment (Plucker)		
Argon discovered (Rayleigh and Ramsay) Neon, krypton, xenon discovered (Ramsay) Gas ionization by collision established (J. J. Thomson)	1900	
Practical process to get the rare gases (Claude) Geiger particle counter devised (Rutherford and Geiger)		Moore luminous tube lamps in use
	1910	Neon lamps introduced by Claude
	1920	Glow-discharge voltage-regulator tubes Grid-glow tube
	1930	
	1940	Geiger-Mueller counter tubes made in quantity

Mercury Pool, Cathode Tubes

Fundamental Research	Approximate Year Publication	Approximate Year Availability	Development
First mercury arc (Way)	1860		
	1880		
Rectifying effect noted in mercury arc (Jamin)			
	1890		
Basic work on mercury arc in vacuum (Arons)			
Gas ionization by collision with electrons established (J. J. Thomson)	1900		
			Mercury-vapor lamp
			Mercury-vapor pool rectifier in glass
	1910		
			Pumped tank mercury-arc rectifiers
Grid control in mercury-pool tube (Langmuir)			
	1915		
High-vacuum condensation pump (Langmuir)			
	1920		
Control of arc current by phase of grid voltage (Toulon)			
Metal-to-glass seal for large diameter cylinders (Housekeeper)			
	1930		
Large strain free alloy seals (Scott and Hull)			
The ignitor for mercury arc cathodes (Slepian)			
Steel-envelope technique			
			Pumped ignitrons
			Sealed steel-envelope ignitrons

Hot-Cathode, Glow-Discharge Tubes—Two-Three-Four-Electrodes, Thyratrons

Fundamental Research	Approximate Year of Publication	Approximate Year of Availability	Development
Loss of electric charge from hot metals (du Fay)	1725		
	1800		
Research on glow discharge in gases (Faraday)	1850		
Hot electrodes lose + and − charges at different rates (Guthrie) Conduction in vacuum from a hot cathode (Edison Effect)			
Gas ionization by collision with electrons established (J. J. Thomson) Basic work on thermionic emission of electrons (Richardson) Electron emission from oxide-coated cathodes (Wehnelt) The grid electrode for control (de Forest)	1900		
	1910		
Grid control in mercury-pool tube (Langmuir)			
			Tungar, low-voltage rectifier
Use of getters in electron tubes	1920		
A-c heater cathode (Freeman) Control of arc current by phase of grid voltage (Toulon) Metal-to-glass seal for large diameter cylinders (Housekeeper)			
Screen-grid tube for radio-frequency amplification (Hull and Willlams) Research on hot-cathode glow discharge (Hull)			Hot-cathode mercury-vapor rectifier The thyratron
	1930		Ultra-violet incandescent lamps
Large strain free alloy seals (Scott and Hull) Steel-envelope technique			Shield-grid thyratron Steel-envelope industrial tubes
			Fluorescent lamps
	1940		

In the case of radio communication, the British scientist, Maxwell, in 1867 enunciated the theory of the transmission of light, heat and radio waves in space. It was 21 years later, and after the death of Maxwell, that Hertz published his paper which confirmed experimentally the theory of Maxwell. After a further lapse of six years, and after the death of Hertz, the Italian engineer, Marconi, transmitted "wireless" messages in 1894. It was about another ten years before there was much actual everyday use of his developments in radio communication. In this example there was a delay of about 35 years between the presentation of a theory and the common use of products based thereon. This was due in part to the lack of organized research and development.

Electronics for radio communication was somewhat more fortunate in this respect. Only about ten years elapsed between the fundamental work of J. J. Thomson on the electron and the fairly common use of the de Forest audion. The really rapid strides in this science took place after 1911, when organized research took up the work. However, as the charts indicate, some phases of what we now consider electronics were slow in getting under way. These charts show very clearly that like many other fields of science many minds working in many lands have contributed to the methods and devices that are now in common use.

It takes a large volume today to cover even the fundamentals of electronics much less its practical applications. However, one simple concept that embraces pretty much the whole field is to consider that, when an electron tube of any sort is incorporated in an electrical circuit, it introduces a gap in that circuit, where the continuous metallic continuity of that circuit is broken, and in its place is substituted a gaseous or vacuum medium across which the electrical current is carried by charged particles. This gap may be only a few thousandths of an inch in length or it may be measured in feet. The fundamental point, however, is that in this gap useful effects occur and it is possible to affect the flow of electrical current in a number of unique ways. It is these unique methods of current control that, in general, make the electron tube the valuable device that it is today.

Looked at broadly, there are four of these unique features:

1. High-vacuum tubes have ability to interrupt, re-establish or vary the current in this gap at tremendously high frequency, up to tens of billions of cycles per second. Therefore, in comparison with most other electrical devices, an electron tube designed for use at high frequency is independent of frequency through a very wide range.

2. Most electrical devices for the control of current effect that control in a step-by-step manner. An electron tube designed for the purpose does it with a degree of smoothness unrivaled by any other method. It is this characteristic that allows it to reproduce music and speech with such perfect quality.

3. The flow of electric current across the gap which is fundamental to all vacuum tubes can be controlled by means of the application of an extremely small amount of electrical power. In many cases, kilowatts of energy may be accurately controlled from a few watts of controlled power. This phenomenon, of course, is spoken of as amplification.

4. Many electron tubes are efficient rectifiers both for heavy currents and extremely high voltages.

Although there are a number of electrical devices that incorporate one or two of these four unique properties, the electron tube in its more common forms combines several to a remarkable degree.

Electronics is a science of extremes. Electron tubes are in common use that

operate at 25 cycles and during the war radar systems were evolved utilizing both transmitting and receiving tubes generating and responding to about 25 billion cycles. Special tubes are available that act as electrometers for detecting currents of the order of 10^{-16} amperes and others are used for controlling the heavy currents to resistance welders involving the conduction of peak values through the tube of about 10,000 amperes. In communication, sensitive measurement tubes are available that can detect and amplify usefully a few millionths of a volt. At the other extreme, the so-called electron accelerators used for X-ray production and in the studies of nuclear physics operate in the millions of volts.

In physical size there is similar extreme range. Tubes have been built about the size of a kernel of grain. At the other extreme, some forms of tank rectifiers are large enough so that a man could move around inside.

It must be admitted that one reason for the versatility and extremes of characteristics exhibited by the various kinds of electron tubes is in a measure accounted for by the breadth of activity which today is covered by the term "electronics". This term has broadened greatly in not too many years. Twenty-five years ago, it was applied almost exclusively to high-vacuum tubes used for radio. Today it has been extended to cover mercury-arc rectifiers, fluorescent lamps, neon signs, cyclotrons and other devices involving the electrical current through a vacuum or gas. There is even a tendency to apply the word to devices in which the conduction is through a solid if this conduction has certain unique properties.

Of late, it has become increasingly apparent that electronics is molding a new career for itself. Over the past many years, engineers and particularly electrical engineers have devoted much effort to the creation of labor-saving devices. These have found their places in the home as well as in industry. As a result, much of the hard physical work formerly done has been eliminated and the human element is now merely the controlling factor. The extent to which this has been done is clearly indicated by the increase of horsepower available to each worker in this country today as compared with not too many years ago.

As has been indicated, electronics will probably enter the picture in a somewhat different way. It will be used to simulate, replace or supplement the mental activities of a human being and the accomplishments traceable to his several senses, such as sight, sound and judgment of temperature. This new concept has now been carried even further. One of the most modern electronic devices is the computer by which complicated mathematical operations can be performed. One of the basic needs in the design of such a computer is a method of storing up impulses so that they may later be combined. This involves the phenomenon of memory, and here electronics is playing an increasingly important function.

Electronic devices or apparatus in which electronics plays an important part are, as has been stated used to simulate the common human senses. Examples of this are the phototube which, like the eye, can respond to varying degrees of illumination; the mircrophone with its amplifier that forms an ear, and the loudspeaker with its amplifier that simulates the voice. More recently, an electronic device has been announced with a sense of smell for certain classes of vapors and smokes.

These provide certain of the basic links by means of which the responses of a human being to different stimuli can be fed into an electrical circuit and made to do things that formerly required a muscular response. In other words,

we are quite rapidly approaching the point where, by the aid of electronics, we can perform many functions that a human being performs that do not actually require reasoning or judgment. Of course, this process has been going on for years to a certain extent. A familiar example is the automatic home heating plant. Here a thermostat detects the drop of temperature in the room and starts the oil burner operating to raise the temperature to the proper value at which time it is automatically turned off. Formerly, one had first to feel chilly and then respond physically by putting more wood or coal on the fire.

Electronics is greatly extending the sensitivity and scope of even simple temperature-regulating systems. But more important, it is extending our several senses to a marked degree. Examples are modern lie detectors, electrocardiographs and a large number of devices that require timing of an operation in microseconds; many orders of magnitude beyond the human perception of time intervals.

This idea of a science to simulate many non-muscular human activities is fairly new, but its ramifications and possibilities may well be staggering in their implications.

There is no reason to believe, however, that electronics will permanently be a dominating science. In popular appeal, nucleonics and atomic energy have already stolen from electronics its prominent position in the public's mind. Even technically other devices and methods from time to time invade fields that once were the strongholds for electronic methods. Examples of this are devices in the semi-conductor field, such as crystal diodes and transistors, which threaten to displace small high-vacuum detecting and amplifying tubes in radio broadcast receivers and repeaters for wire telephony. It is true that many physicists consider this new class of device electronic, although it is a far cry from the older and more restricted definition. Mr. D. G. Fink, Editor of the publication *Electronics,* presented a most interesting discussion on this point at the 1948 National Electronics Conference in Chicago, speaking on the subject "Decline and Fall of the Free Electron." He pointed out that all sciences as they pioneered and spread their influence experienced other factors that changed or narrowed their scope.

There is every reason to believe, however, that, when the Journal celebrates its 150th year of publication, electronics will have extended to a wider field and will be functioning in ways in which we now little dream.

STUDIES ON FLY-ASH EROSION

ACKNOWLEDGMENT

This article by Messrs. M. A. Fisher of the Armour Research Foundation and E. F. Davis of the Institute of Gas Technology is reprinted from "Mechanical Engineering" for June 1949. It deals with tests of metal erosion caused by impingement of solid particles suspended in a rapidly moving stream.

INTRODUCTION

One of the chief difficulties anticipated in the use of pulverized coal as a fuel for the gas turbine is the possibility of serious erosion of turbine blades and other metal parts by the suspension of fly ash in hot combustion gases. However, there appears to be no published information to date on the amount and nature of erosion by fly ash under actual turbine conditions. The Locomotive Development Committee of Bituminous Coal Research, Inc., has been vitally concerned with this problem in connection with the development of a coal-fired gas-turbine-driven locomotive. Therefore this committee has sponsored the work which is described in this paper, and which was carried out in the laboratories of the Institute of Gas Technology.

The erosion of metals through the impingement of solid particles suspended in a rapidly moving gas stream is an extremely complicated process which at present cannot be described in exact terms. It appears likely that, in most practical cases, erosion can take place through several different mechanisms, depending upon the properties of the eroded material and of the impacting particle, as well as upon local conditions at the microscopic point of impact. Under certain conditions, at least, it can be shown that the momentary pressure developed by the impact of a small particle at a velocity of several hundred feet per second may be sufficient to exceed the ultimate strength of any metal.[1] On the other hand, some experimental evidence indicates that, at least under some conditions, the amount of erosion depends primarily on the hardness of the eroded metal. Thus Gardner found that the erosion of turbine blades by water droplets in a special testing machine was a function of the hardness of the blade material, the harder metals being more resistant to erosion.[2] The importance of other factors, such as elasticity and fatigue resistance, is indicated by the erosion resistance of materials such as rubber.

The high operating temperature of gas-turbine blades introduces special problems in connection with erosion by solid particles. The oxide film which is formed on metal surfaces at high temperatures may well be more brittle and more susceptible to erosion damage than the underlying metal. If this surface film is removed by erosion, exposing more metal to oxidation, then the repetition of this process might lead to a very rapid loss of metal. In addition, the heterogeneous nature of some turbine alloys complicates the situation because the relatively minute particles of fly ash may show a preferential

[1] "Impact Cleaning," by W. A. Rosenberger, The Penton Publishing Company, Cleveland, Ohio, 1939.

[2] "The Erosion of Steam Turbine Blades," by F. W. Gardner, *Engineer*, vol. 153, 1932, pp. 146, 174, and 202.

attack on some constituents of the metal structure, resulting in the weakening of stressed parts. In studying the erosion of turbine blades by fly ash at high temperatures, it is thus necessary to investigate possible structural changes and localized damage, as well as the over-all loss in metal weight.

Very little appears to be known about the dynamics of the movement of small suspended particles through a system as complicated as a gas turbine. Equations for the trajectories of particles in relatively simple flowing systems have been given by Lapple and Shepherd[3] but no way is known of applying these results to the case of erosion in gas turbines. The actual paths of ash particles carried by the gas stream through the turbine will be a complicated function of gas velocity and temperature, particle-size distribution, and density of the particles, as well as the specific design of nozzles and blades and the velocity of rotation. It is impossible to predict how many of the fly-ash particles actually will strike the blades, at what relative velocity, and at what angle. For particles which actually impinge on a solid surface, the pressure exerted is highly dependent also on the shape of each particle and its elastic properties.

Since preliminary information was urgently needed on the probable course of erosion by fly-ash particles, experiments were designed to simulate turbine conditions closely. At the same time, the experimental apparatus was kept as simple and as flexible as possible, so that a rapid survey could be made of the chief variables which will determine the amount of erosion by fly ash in a coal-burning gas-turbine locomotive. As will be shown later, a number of interesting and unexpected results were obtained. In general, it appears that erosion can be controlled, but careful attention is required to several factors which were not previously known to be important.

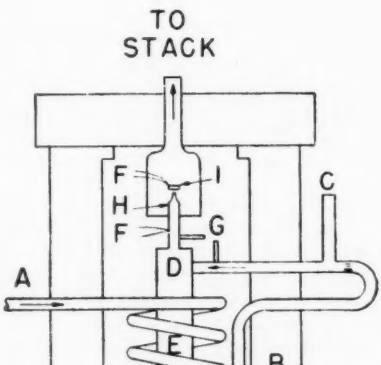


Fig. 1.—Apparatus for fly-ash erosion test at high temperature. (A, Compressed air; B, insulated electric furnace; C, dust feed; D, Aerotec dust collector; E, dust-collection chamber; F, thermocouple; G, pressure taps; H, nozzle; I, specimen.)

EROSION-TEST APPARATUS

The type of apparatus used for running erosion tests under a variety of condtions is shown diagrammatically in Fig. 1. Compressed air, regulated by a pressure-reducing valve, was metered by a calibrated orifice. The air then passed through a heat-exchanger coil consisting of half a dozen turns of 1-in. 18-8 stainless steel pipe, packed with porcelain balls to assist in heat transfer. The heated air was brought out of the furnace as shown for the introduction of fly ash through the vertical pipe C. The fly ash entered at a constant predetermined rate, and was

[3] "Calculation of Particle Trajectories," by C. E. Lapple and C. B. Shepherd, *Industrial and Engineering Chemistry*, vol. 32, 1940, pp. 605-617.

dispersed into individual particles by the high-velocity jets of heated air issuing from three fine openings in a plug inserted in the air line just ahead of the dust feeder. The ash-laden air was returned to the furnace and proceeded to a miniature Aerotec dust-separating tube, enclosed in a stainless-steel cylinder as shown. Here the coarser particles of fly ash were separated from the air and dropped into the storage space E. The Aerotec dust separator used will be more fully described in a later section.

In some of the erosion tests, the apparatus was modified by extending a pipe from the Aerotec dust outlet through a hole in the bottom of the furnace to a dust-storage hopper underneath. The pressure drop across the Aerotec tube was measured by a water manometer attached to the pressure taps G. The air temperature between the outlet of the Aerotec tube and the nozzle H was measured by a thermocouple F, inserted through the pipe wall and fastened by means of high-temperature silica cement.

At the beginning of the tests, the readings of the thermocouple F were checked against a fully shielded thermocouple placed in the air jet above the nozzle mouth. The interchangeable nozzles H were machined from stainless steel and served as supports for several types of specimen holders. A thermocouple F, as shown, measured the temperature of the erosion test specimen; since the whole apparatus was enclosed in an insulating structure, the temperature of the specimen was always close to the temperature of the fly-ash suspension in air. After striking the specimen, the air was exhausted through a pipe stack as shown. Part of the fly-ash content remained on various parts of the enclosure around the nozzle and erosion specimen; the remainder of the fly ash, after passing through a sufficient length of stack for cooling to a convenient temperature, was removed by a filter bag or an electrical precipitator. Thus all of the fly ash which passed through the apparatus was available for examination after each test.

In those tests where it was desired to test the effects of "raw" fly ash, that is, fly ash as received without any preliminary separation of the coarser particles, then the whole assembly containing the Aerotec tube separator could be removed and replaced by a simple duct which carried the fly-ash suspension to the nozzle. The furnace was heated electrically; both manual and automatic temperature control were conveniently used on different sets of apparatus. The relatively small demands of the apparatus for power and compressed air made it possible for several erosion tests to be run simultaneously. Erosion tests at room temperature were carried out also in apparatus similar to the foregoing, except that the furnace and insulation were omitted.

Fly-Ash Feed. Most of the erosion tests were carried out with samples of fly ash obtained from various power plants operating on pulverized coal. In all, ten samples of fly ash were used, representing various Eastern and Mid-western bituminous coals. Microscopic examinations, chemical analyses, and screen tests were carried out on the fly ash, but no detailed correlations of these factors with erosion could be obtained. However, a number of interesting general trends were observed, as will be described in a later section. It was determined that all of the fly ash used consisted chiefly of the spherical particles characteristic of fused ash, and that the general observations with regard to erosion remained valid for all of the various samples of fly ash used.

Differences in the particle-size distributions of the fly-ash samples were partially ironed out in those tests where an Aerotec tube was used to remove the coarser particles of fly ash before

impingement upon the test specimen. The Aerotec tube is a cyclone type of dust separator. We have conducted tests on commercial models of Aerotec tubes of 2 in. and 3 in. diam, and have determined that these cyclones are capable of removing over 90 per cent of a fine pulverized-coal fly ash. Aerotec tubes were used in the erosion tests to determine the probable effect on turbine erosion if a high-efficiency separator is used to remove all but the finest particles of fly ash. The Aerotec tubes used in the erosion tests were ¾ in. diam and made of stainless steel. In preliminary tests, the conditions for operating these miniature tubes were established so as to obtain the same fly-ash-separating efficiency as with the larger Aerotec tubes. Thus at room temperature, the tubes were operated at 2 to 4 in. of water pressure drop, passing 2 to 3 cfm of air.

As an alternative to the use of the miniature Aerotec tubes, and to check the results, some of the erosion tests were also carried out with fly ash which had previously passed a regular 3-in. Aerotec tube. The procedure in these cases was to pass a quantity of fly ash through the larger Aerotec tube, collecting all fly ash which passed the separator in a large close-woven filter bag; this fine dust was then used in an erosion apparatus which did not, in such tests, include any fly-ash separator.

One of the most important requirements in a laboratory apparatus for testing dust erosion is to feed the dust into the air at a uniform rate in such a way that the dust is dispersed into individual particles, and the particle-size distribution does not vary with time. The type of dust feeder developed for the erosion tests is shown in Fig. 2. The operation of this feeder depends on the vibratory motion induced by a Burgess Vibrotool, and the rate of dust feed is controllable readily by adjusting the vibration amplitude.

The vibrator, which is commercially available, is a simple electromagnetic device which operates on 110-volt a-c to give 7200 vibrations per min. Under the action of the vibrator, a steady stream of dust moves along the lower horizontal tube until it falls into the high-velocity jets of compressed air which disperse the dust into individual particles. The dimensions of the apparatus are not critical, except that the size of the horizontal dust-feed tube limits the range of feed rates available for any particular dust. Although the feeder may be constructed of smooth metal tubing, we have found it convenient to use glass feeders for pressures up to 30 psig, so that the movement of the dust can be observed readily and adjusted by manipulation of the amplitude control on the vibrator.

We have used a number of feeders of this type for feeding different kinds of dusts at rates varying from less than 0.1 gram per min. to 50 grams per min. Where dust is to be fed into a system in which the pressure is close to atmospheric, it is convenient to modify the apparatus by omitting the pressure-equalizing tube and opening the top of

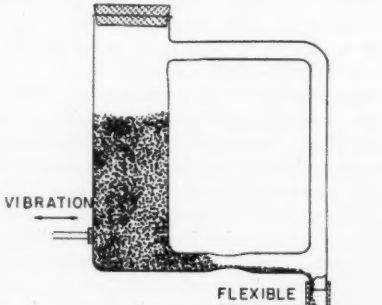


FIG. 2 DUST FEEDER

the dust hopper to the atmosphere. In such cases, the dust is introduced into the test system through the suction opening of a compressed-air ejector which does an excellent job of dust dispersion. When first setting up a dust feeder for a particular apparatus, it is also convenient to make up a dust hopper with a number of interchangeable feed tubes, so that the best size of tube for the particular application may be chosen by trial. The feeder is then calibrated by collecting and weighing the portions of dust fed in a number of equal successive time intervals. Unless a dust is particularly free-flowing it is usually advisable to dry it thoroughly just before use, and to eliminate lumps by passing the dust through a sieve which is just coarse enough to pass all of the particles.

The dust feeders used in the erosion tests had hoppers 2¼ in. diam and 12 in. high, with a capacity of about 600 g of fly ash per loading. The horizontal feed tube was 6 in. long and ½ in. ID, with a smooth constriction to ¼ in. diam in the center. The constriction in the trough is an important feature because it produces a constant level of dust in the portion of the tube beyond the constriction and thus provides a constant rate of dust feed.

The question whether a suspension of dust in air is well dispersed into individual particles rather than clumps can be settled only by sampling and examing the particles as they actually exist in the suspension. For this purpose, a small laboratory type of electrical precipitator was used to obtain samples of the fly-ash dispersion produced by the dust feeder. The particles were deposited directly from the air onto a thin glass cover slip which could then be examined microscopically.

Fig. 3 shows a photomicrograph, at a magnification of 500 diam, of a sample obtained in this way from a fly-ash suspension produced by the dust feeder described. For purposes of comparison,

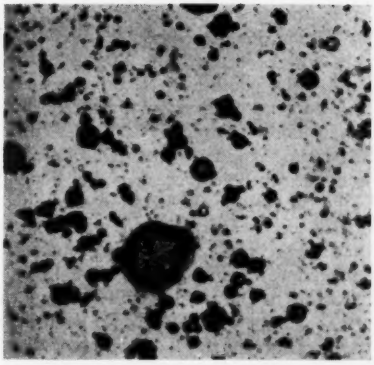


Fig. 3.—Pulverized-Coal Fly Ash. (Sample prepared by precipitation from a suspension in air; X200.)

Fig. 4 shows the appearance of fly-ash particles which have passed through an Aerotec-tube dust separator at a temperature of 970 F without being precipitated. Similar photomicrographs prepared by a number of special techniques were used throughout the erosion work to study the state of dispersion as well as the particle-size distributions and shapes of the fly-ash particles. It may be noted in passing that the largest particle visible in Fig. 4 has

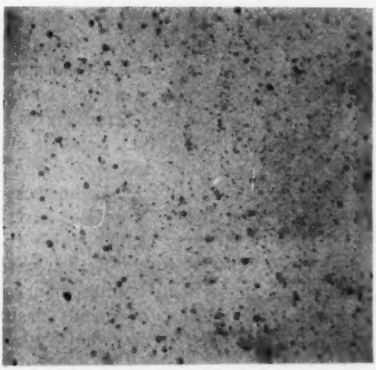


Fig. 4.—Fly Ash in Aerotec-Tube Exhaust. (Sample prepared by precipitation from exhaust gas of an Aerotec tube operating at 970 F; X200.)

a diameter of about 7 microns, representing the maximum size of particle which escaped the dust separator under the conditions of this particular experiment. Other photomicrographs have shown conclusively that many particles smaller than this are removed by an Aeortec separator, depending probably on the position of the particles in the air stream entering the separator. The over-all dust-separating efficiency of the Aerotec tube in each erosion test was determined from the total weight of dust fed, the weight of dust caught in the Aerotec hopper, and the weight of dust recovered in the filter bag or electric precipitator beyond the erosion test nozzle and specimen.

Nozzles and Erosion Specimens. One of the chief factors determining the erosion of metals by fly-ash suspensions is the velocity of the impinging air stream. In this series of experiments, a range of velocities from 150 fps to 1040 fps was used, but most of the erosion tests at high temperature (1050 F to 1350 F) were run with air velocities between 500 fps and 850 fps. In the large gas turbines projected for locomotive service, the air velocities relative to the moving blades will be approximately 500 fps under normal operating conditions, but will vary considerably over the full cycle of operation. The air velocities were calculated for the erosion tests on the assumption of ideal conditions and were based on published tables of the properties of air. In view of the other experimental uncertainties, no attempt was made to apply any corrections for the effect of the suspended fly-ash particles on the air velocity. It was realized also that the actual velocity of the fly-ash particles at the moment of impingement is a complicated function of nozzle design as well as of particle size, density, and shape of the particles; in general, it cannot be assumed that the velocity of the particles is the same as that of the conveying air. The same situation of course will apply in the gas turbine and will be further complicated by the effects of centrifugal forces on the particle trajectories.

The nozzles used in the erosion tests were of simple convergent design, machined from 18-8 stainless steel, and readily interchangeable for the various experiments. The throat diameter varied from 0.101 in. to 0.275 in., and was determined by the desired air capacity which in turn was based on the volumetric air flow necessary to give the correct pressure drop and efficiency in the Aerotec dust separator. Although the rate of fly-ash impingement thus varied according to the conditions of the individual erosion tests, the final results were compared on the basis of the erosion produced per unit weight of fly-ash impinged. The effects of absolute nozzle size were determined in a separate series of tests in which no Aerotec separator was used, and the nozzle diameter therefore could be varied at will.

A typical assembly of nozzle, specimen holder, and specimen is shown in Fig. 5. Here, the specimen is set with its surface perpendicular to the axis of the air jet. Also visible is the thermocouple used to

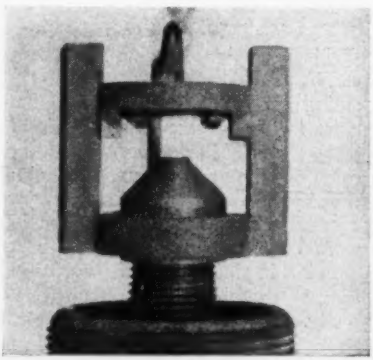


Fig. 5.—Nozzle, Specimen, and Specimen Holder Arranged for Perpendicular Impingement.

measure the temperature at the back of the specimen. As shown in Fig. 6, the specimens could be rotated to any desired angle with respect to the axis of the air jet. This view also shows the erosion test specimen consisting, in this case, of a disk of metal 1 in. diam and ⅛ in. thick. Other test specimens were made in the form of thick rectangular blocks and were supported in a similar manner.

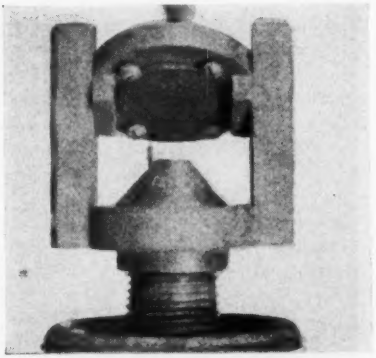


Fig. 6.—Nozzle, Specimen, and Specimen Holder Arranged for Impingement at an Acute Angle to Face of Specimen.

A simple support for small Vitallium turbine blades is shown in Fig. 7. The blades could be positioned at different distances from the nozzle and at various angles to the axis of the air jet in order to test the effects of fly-ash impingement on curved surfaces, such as will be found in an actual turbine.

Another type of erosion test specimen used consisted of turbine alloy pieces machined in the shape of standard stress-rupture test specimens. By means of a special yoke and lever arrangement, these specimens were kept under a continuous tension of 15,000 psi while being bombarded with fly ash at a temperature of 1350 F. The effect of fly-ash impingement was determined both by weighing the specimen before and after treatment and by running standard stress-to-rupture tests on the treated specimens and on similar blank specimens.

In order to eliminate variations due to the nature of the surface finish on erosion specimens, all test disks were given a standardized metallographic polish before erosion testing, and metallographic examinations were made on some of the specimens before and after fly-ash treatment. Records were kept of weight changes of the specimens during test, and dimensional changes were followed with sensitive gages and by microscopic measurements. Rockwell hardness measurements were also made. Care was taken not to introduce stresses in the process of cutting specimen disks, and specimens were given a stress-relieving heat-treatment whenever necessary. The metals used for the erosion tests included a carbon steel, cast Vitallium, and the following special alloy steels: Timken 16-25-6, Universal-Cyclops 19-9DL; and Allegheny-Ludlum S-590 and S-588.

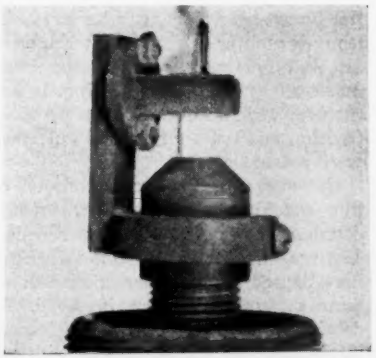


Fig. 7.—Nozzle, Specimen, and Specimen Holder for Small Turbine Blades.

TEST RESULTS

The first series of erosion tests was carried out at room temperature using "raw" fly ash, that is, a sample of fly ash as obtained from the electrostatic

precipitator of a large pulverized-coal-burning furnace. A preliminary set of experiments showed that the quantitative amount of erosion observed was highly dependent on a large number of factors which would have to be closely controlled. Thus Fig. 8 shows the amount of erosion of a Vitallium disk specimen as a function of the amount of fly ash impinged on it with a jet velocity of 1040 fps. The nozzle throat diameter was 0.101 in., and the specimen

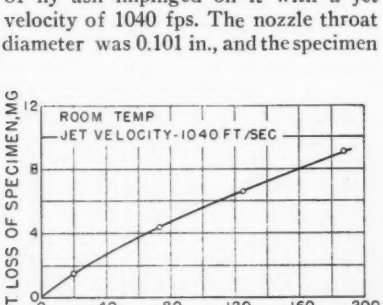


Fig. 8.—Erosion of a Vitallium Specimen as a Function of Weight of Fly Ash Impinged.

face was perpendicular to the axis of the nozzle and at a distance of ¼ in. from its mouth. At regular intervals, the air flow was shut off and the specimen was removed for weighing. It was then replaced accurately in its previous position and the air flow and dust feed were started again.

Obviously, under the conditions of this experiment, the rate of erosion decreased as the experiment proceeded. The reasons for this behavior were not investigated in detail, but a number of factors may have been involved. As erosion proceeded, a cavity was formed in the face of the specimen, with resulting changes in both the angle and distance of impingement. There was also the increased possibility for some of the fly-ash particles to remain temporarily in the cavity and thus cushion the impact of succeeding fly-ash particles. Morever, metallographic examination of eroded Vitallium specimens showed that there had been a preferential removal of the softer components of the metal structure, leaving many of the harder dendritically arranged particles of a harder component protruding from the surface. The nonhomogeneous structure of the metal was confirmed by examining polished and etched surfaces of specimens before erosion.

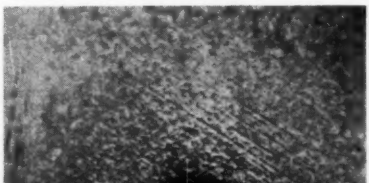


Fig. 9.—Erosion Pit in Vitallium Specimen.

Fig. 9 shows the appearance of a deep erosion pit in a Vitallium specimen, produced by the impingement of unseparated fly ash at 1040 fps and room temperature. The characteristic striated structure is clearly visible, and close examination reveals small grains of hard material adhering to the eroded surface.

The rate of erosion of Vitallium by unseparated fly ash at room temperature increased with increasing jet velocity, as shown in Fig. 10; the rate of increase was especially high at jet velocities approaching sonic velocity. Each value on this curve was obtained on a separate specimen, treated from a nozzle of 0.101 in. diam at a distance

of ¼ in. The total amount of fly ash impinged was about 130 g for each specimen, and the fly-ash concentration in the air stream was kept between 2 and 3 grains per cu ft.

The effect of nozzle-to-specimen distance is shown in Fig. 11 for a jet velocity of 850 fps at room temperature. As in the previous series of tests, the specimens were Vitallium disks placed perpendicular to the axis of the nozzle, and unseparated fly ash was used. The reasons for the rapid increase in erosion with increasing nozzle-to-specimen distance are not clear from the data available. The larger distances allow more time for accelerating the ash particles to the velocity of the air stream; at some critical distance from the nozzle mouth, the jet velocity must begin to decrease, and on approaching the specimen face the air velocity must undergo drastic changes in magnitude and direction. The lag between the air velocity and the velocity of an individual ash particle depends on the physical properties of the particle. With a heterogeneous sample of fly ash, the situation rapidly becomes too complicated to warrant an attempt at theoretical analysis.

The preliminary series of experiments with unseparated fly ash indicated the difficulty of any quantitative interpretation of erosion-test results unless a large number of variables

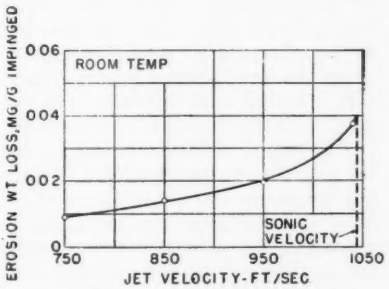


Fig. 10.—Erosion of Vitallium by Fly Ash as a Function of Jet Velocity at Room Temperature.

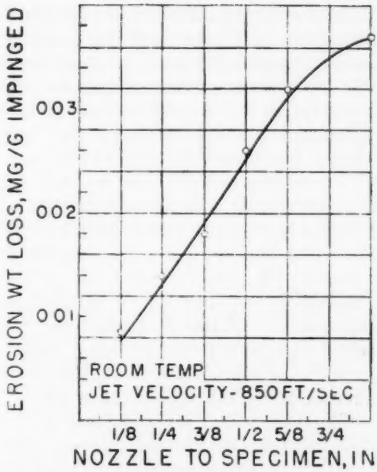


Fig. 11.—Erosion of Vitallium by Fly Ash as a Function of Distance Between Specimen and Nozzle Mouth.

were carefully controlled. Not only must the exact conditions of impingement be specified, but the erosion process must also be studied with due regard to the microstructure of the particular metal specimens used. The major effort of the erosion-test program was thereafter directed toward studying the behavior of a number of turbine alloys on bombardment with many kinds of fly ash under a variety of conditions likely to be encountered in actual coal-fired gas-turbine operation. Altogether, some 200 erosion tests were made, supplemented by physical and chemical studies of the fly ash and metal specimens. Space does not permit a detailed discussion of all the results, and only the general conclusions can be given.

In contrast to the erosion tests carried out with raw fly ash at room temperature, when an Aerotec tube was used to remove the coarser particles of fly ash, it was found that a persistent deposit of ash particles was formed on the erosion targets. This deposit protected the surface of the specimen against erosion. However, even when

the deposit was removed mechanically from the specimen face at frequent intervals during a test, it was found that the amount of erosion produced by the very fine ash particles which passed through the dust separator was less than 10 per cent of the erosion produced by the same weight of raw fly ash, the exact amount of erosion depending on test conditions and Aerotec efficiency. Since the Aerotec separator removed 90 per cent or more of the original fly-ash loading, it is obvious that the use of the dust separator resulted in a 99 per cent or better reduction in erosion, based on the total amount of fly ash fed during a test.

The appearance of a typical heavy deposit of fly ash formed at room temperature by impingement at a velocity of 1040 fps is shown in Fig. 12. It was

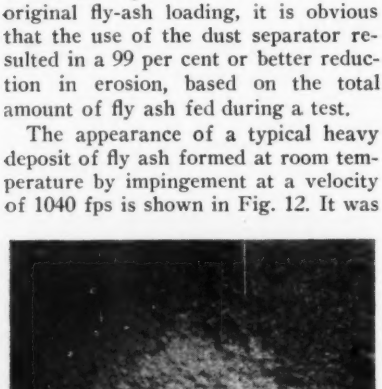


Fig. 12.—Fly-Ash Produced at Room Temperature.

established that the formation of the deposits did not depend on the presence of oil or other impurities in the compressed air. However, pretreating the fly ash by heating it at 1400 F for several hours did reduce the tendency to form deposits and resulted in increased amounts of erosion. Since pretreatment of the fly ash removed the last traces of carbonaceous matter, this may indicate that the presence of relatively soft or plastically deformable material in the fly ash plays a role in deposit formation. However, the full explanation is apparently much more complicated, since there is evidence that the pretreatment by ignition also resulted in recrystallization and chemical reaction of some of the inorganic constituents of the fly ash. Morever, many purely inorganic materials give deposits under similar conditions of impingement.

A series of tests were made in which thin deposits of fly ash were produced by impingement on thin glass cover slips. It was found that about the same proportion of fly ash adhered to the glass as to metal specimens. Microscopic examination of the deposits on the glass cover slip showed the characteristic, spherical, transparent particles of ash adhering to the glass surface. There was no evidence of fragments produced by shattering of particles either on the glass surface or in the air stream beyond the target, nor was there any appreciable number of particles which appeared as if they might have been flattened or plastically deformed by the impact on the specimen. The smaller ash particles adhered preferentially to the glass, and the primary deposit on the glass consisted mostly of particles smaller than about 2 microns. This is in keeping with the behavior observed in dust-sampling instruments and indicates that the same forces of physical adhesion are involved. Particles which have sufficient kinetic energy on impact to squeeze out the gas film at the specimen surface become attached to the surface, and adhere to the surface the more tightly the higher the surface-to-mass ratio of the particle.

High-Temperature Erosion Tests. The chief feature of all erosion tests at high temperature (800 F to 1350 F) was

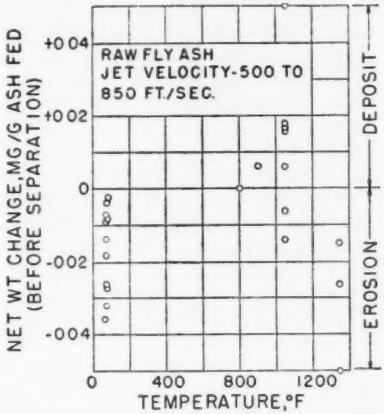


Fig. 13.—Net Weight Change of Specimens in Erosion Tests at Various Temperatures. (Raw fly ash; various conditions of impingement: jet velocity, 500 to 850 fps.)

the formation of hard tenacious coatings or deposits on the specimens. The exact amount and nature of the deposits varied widely according to the fly ash used and the conditions of impingement. In many cases it was found that both deposit formation and erosion took place on different parts of the same specimen, so that the net result varied from a considerable loss of weight of the erosion test specimen under some conditions to rapid weight gains under other conditions. In general, it was found that deposit formation was associated with the impingement of relatively fine ash particles, smaller than about 10 microns diam, while coarser particles tended to remove any deposits present on the specimen face and to produce erosion of the metal.

While several series of erosion tests were carried out to determine some of the factors involved in erosion at high temperatures, only the general results will be taken up at this time. Fig. 13 shows the net weight change of various metal specimens after the impingement of unseparated fly ash under a variety of experimental conditions. Each point on the graph is the result of a separate erosion test. It is seen that while there was often considerable deposit formation by raw fly ash, particularly around 1000 F, in general, it may be expected that this type of fly ash would create a definite erosion problem.

Fig. 14 shows a similar graph for the results of tests carried out with Aerotec-separated fly ash. Here it is seen that the chief problem due to the fly-ash impingement was deposit formation rather than erosion of the metal specimen. The tests at room temperature which resulted in weight losses were all carried out with pretreated or ignited fly ash, as was also the test which showed the greatest weight loss at 1055 F.

The results of a set of high-temperature erosion tests carried out under uniform conditions of impingement is

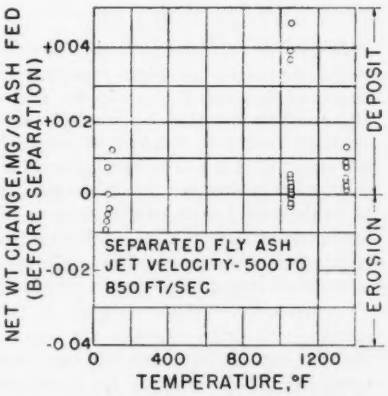


Fig. 14.—Net Weight Change of Specimens in Erosion Tests at Various temperatures. (Aerotec-separated fly ash; various conditions of impingement; jet velocity, 500 to 850 fps.)

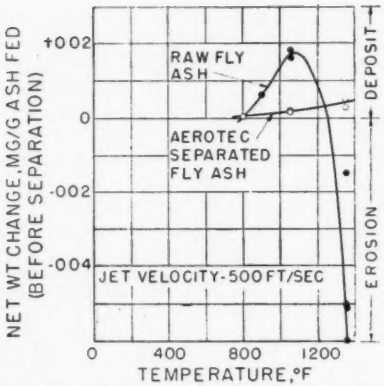


Fig. 15.—Weight change of Timken Alloy Specimens in Erosion tests at High Temperatures.

shown in Fig. 15, to illustrate the observed effect of removing the coarser particles of fly ash. At the top turbine operating temperature of 1350 F, the coarse particles removed any deposit which may have been formed faster than it could be built up by the relatively fine ash particles, resulting in a marked erosion. Where the fly-ash separator was used, there was no erosion, and the amount of deposit increased with increasing temperature.

High-Temperature Deposits. The deposits produced at high temperature consisted of a hard ceramic-like material ranging in color from a light tan, through various shades of reddish brown, to a dark-red almost black color. Most of the deposits adhered so strongly to the metal surface that they could be removed only with difficulty by using a sharp knife-blade. The main portion of the deposit was generally found in a roughly conical mound on the specimen directly opposite the nozzle mouth, but a thin coating extended over the whole surface of specimen disks 1 in. diam. Many of the deposits showed concentric rings of varying thickness and color. This structure was apparently connected with resonance and vibration phenomena in the air jet, but no detailed investigation of the subject was carried out.

The general appearance and properties of the high-temperature deposits suggested that the fly-ash particles actually were sintered together, even at temperatures as low as 800 F. To check on the sintering temperatures of gross samples of fly ash under atmospheric pressure, samples of the various types of fly ash available were heated in a furnace to various temperatures between 800 F and 1600 F. Color changes in the fly ash were observed after heating at 800 F for 4 hr, indicating the beginning of chemical changes in the ash, but no appreciable sintering occurred below 1300 F. It appears therefore that the sintering of the fly ash in the deposits must be helped by the pressures developed during impingement as well as by the selective concentration in the deposit of the more plastic constituents of the fly ash.

Spectrographic analyses of a deposit formed by impingement of fly ash at 1055 F showed a higher concentration of calcium and lower concentrations of aluminum and silicon in the deposit material as compared with the original fly ash. X-ray analyses confirmed the fact that calcium sulphate showed a

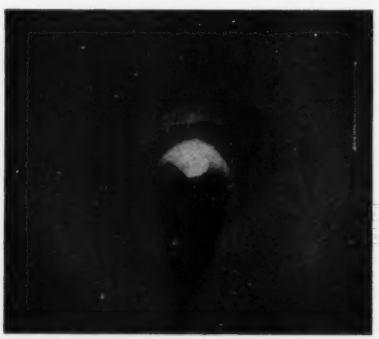


Fig. 16.—High-Temperature Fly-Ash Deposit. (The raised conical deposit in center was surrounded by area containing a flat deposit.)

Fig. 17.—High-Temperature Fly-Ash Deposit. (Entire surface of specimen was covered by deposit. Note irregular mound in center.)

Fig. 18.—High-Temperature Fly Ash Deposit. (Flat plateau in central region, shading off to a light film over remainder of specimen surface.)

marked increase in concentration in high-temperature deposits. It was also found that the iron present in the form of magnetite in the fly ash was completely oxidized to hematite in the deposit.

The appearance of several typical high-temperature fly-ash deposits is shown in Figs. 16, 17, and 18. Although the deposits usually adhered tenaciously to the underlying metal, it was found possible to remove them completely by any one of several methods. Thus deposits could be removed completely by controlled impingement of ordinary fly ash either at room temperature or at 1350 F, without any appreciable damage to the metal specimens. An effective chemical method of deposit removal was found in the use of an inhibited acid solution which loosened the deposit on immersion for a few hours. After thus removing high-temperature deposits from specimens, it was found that the loss of metal was negligible and a good surface was restored. Sectioning and metallographic examination of the specimens showed no evidence of any harmful effects on the metal structure due to the fly-ash impingement or the chemical treatment.

The valuable assistance of the following individuals is gratefully acknowledged: O. Zmeskal and B. S. Swanson, Jr., for metallurgical consultation; W. C. McCrone, Jr., and members of the Analytical Section of Armour Research Foundation for photomicrographs, electron micrographs, and spectrographic analyses; S. L. Axelrood and J. C. Foster for assistance with some of the experimental work.

Acknowledgment is made to Allis-Chalmers Manufacturing Company for the use of an unpublished series of reports on some phases of the application of pulverized coal to the gas-turbine cycle which has been made by Battelle Memorial Institute on a research project for Allis-Chalmers.

SINGING PROPELLERS

ACKNOWLEDGMENT

This article by Mr. William Lambie is part of a paper delivered by him at a meeting of the Southern California Section of the Society of Naval Architects and Marine Engineers held at Wilmington, California in September 1949.

SYNOPSIS

It is believed that any usual marine propeller will vibrate if operated at a slip ratio lower than that which corresponds to maximum efficiency.

In the Paper a distinction is made between "whistling" and "singing" as applied to noisy marine propellers and a possible reason advanced for "whistling". It is noted that any such propeller may whistle or sing, or whistle *and* sing.

It is shown that a propeller having either ogival or airfoil sections, and whether mass-balanced or not, may whistle at any slip ratio if the trailing edges of the blades are not properly formed. Also a mass-balanced propeller operating at low slip will vibrate but will not necessarily whistle or sing; the vibration may be inaudible.

Prior to the introduction of the Airfoil section, propellers generally had been made with the shape of the blade disposed symmetrically about a straight line from root to tip, with the point of maximum thickness and the centroid of each section lying on this line; they were thus mass balanced about that straight line. The first "singing" propeller seems to have been one installed on the *Athelfoam* built by Cammell, Laird & Co., in England in 1930. They became really noticeable only after propellers with airfoil sections had come into quite general use. They were brought to the attention of Naval Architects and Marine Engineers principally by Mr. Harry Hunter, B.Sc.,[1] who pointed out that although called "singing" propellers, a more correct term would be "noisy" propellers, as in some of the ships the noise has been anything but "harmonious".

Quoting from the Aeroplane Industry, Mr. Hunter says "Airscrew noise is a very complex subject, and at present there are thought to be four kinds of it, namely (1) Flutter Noise, (2) Supersonic Noise, (3) Drag Noise, (4) Thrust Noise. Flutter noise is due to vibration of the blades and is evidence of structural inadequacy. Flutter must be prevented or the airscrew will fail structurally. Supersonic noise only arises when the tip speed approaches the velocity of sound. It is always associated with loss of efficiency, and is eliminated by keeping the tip speed well below the velocity of sound in air. Drag noise is due to either compressibility or vorticity effects and is mainly of high frequency. Thrust noise arises from the rotary pressure field associated with the airscrew and is stated to be the most disturbing kind of noise".

[1] "Singing Propellers." Harry Hunter, O.B.E., B. Sc., N.E.C. Inst., Vol. LIII, 1937.

In a previous paper we stated that "only once had we found an ordinary ogival sectioned propeller to "whistle" and that one was so worn down at the edges by erosion on the blade faces that I believe each blade was fluttering"[2] However, within the past year we have had a number of small propellers brought to our attention on account of their "whistling", although they were not of airfoil type, but had the general round back Ogival blade sections.

Most of these propellers, in our opinion, were of the correct dimensions for the Speed, R.P.M., and Power involved, and seemed to be operating at the slip corresponding to maximum efficiency. In searching for possible causes of the "whistling", no signs of erosion were noticed, but the trailing edges from Hub to Tip and the leading edges near the Tips were found to be somewhat square, that is, not rounded off. The noise emitted by these propellers was reported as a shrill whistle, and it disappeared when the edges had been ground quite sharp.

Since our experience with airfoil sectioned propellers caused us to think and state, that propellers did not sing or whistle when they were operating at the correct slip angle, we were quite surprised to receive that very complaint with regard to those small propellers. We had had no such troubles with our own ogival sectioned propellers, but they had quite sharp edges. It is thought possible that the water may have been flowing in streamline form over both sides of the blades of these "whistling" propellers without forming eddies, until it reached the trailing edge. Here, due to the relatively thick, square edge, the water would break away from streamline form and a more or less vacuous space would be left where eddies and bubbles would be formed. These bubbles, as the blade edge moved away from them, would collapse, but would not do so *on* the blade. They would be collapsing in water, and there would be no water-hammer blows on the blade, so it would not be vibrated. The occluded air would rush out of the water into the vacuous space left at the trailing edge and this entrainment of the air might conceivably be the cause of the "whistling" which would be the only sound heard.

Should we agree that this may be a fact, then it would appear that the material of which a propeller may be made will probably not be a factor contributory to "whistling".

In the past we have used the terms "whistling" and "singing" quite loosely to designate the sounds coming from a "noisy" propeller, but now we believe that there may be some propellers that "whistle", some that "sing", and still others that "whistle" *and* "sing". It therefore seems important that we distinguish between "whistling" and "singing" as applied to propellers.

Might we not conclude that in cases like those just mentioned, the propellers could be termed "whistling" propellers? They are not necessarily operating at incorrect slip, but whistle when the R.P.M. exceeds a certain amount because of the form of the edges. This noise may be akin to the drag noise mentioned in connection with air screws.

On page 190 of the original edition of his *Speed and Power of Ships,* Admiral Taylor, in discussing cavitation, wrote, "The case of cavities over the blade faces is different. They have no redeeming feature." It seems a pity that this statement, which we believe to be axiomatic, has not been included in the later editions of that monumental work. Face erosion we have always found to be accompanied by more or less serious vibration, and we find more propellers cavitating and vibrating because of operation at low slip than

[2] Cavitation and the Propeller of Maximum Efficiency." W. Lambie.

from lack of head or too high tip speed. We feel that such cases should not be dignified by any reference to the term Cavitation; they are just not of the correct dimensions for the conditions under which they may be working. It may be significant to note that in our own experience, "singing" propellers are never free from erosion on the blade faces. To us this indicates that such propellers are operating at a slip lower than that corresponding to maximum efficiency.

In the paper already referred to,[1] are given particulars of a number of cases of "noisy" propellers which were serious, and led to an investigation. They were referred to as Ship (A), (B), (C), (D), (E), and (F). Among them was that of a single screw passenger vessel 256′ x 36′ x 23′ driven by a triple expansion engine 22″ x 34½″ x 39″ stroke and developing 1900 I.H.P., at 102 R.P.M., giving the vessel a speed of about 13 knots. On this case, Ship (F), the Author reported that "in order to reduce the disturbing noise (from the propeller) which was annoying to the passengers, seventeen 1″ lead rivets were drilled in each blade. The row of rivets followed the edge of the propeller blade at a distance of 2 inches. The distance between the rivets was 4 inches. The result of this actually reduced the noise to a certain amount . . . very soon the lead rivets got slack and fell out, and when two or more rivets had fallen out, the noise increased in strength. It was noticed that it was always on the following edge that the rivets fell out. It was also noticed that when more than two rivets had fallen out there was a singing noise *After The Engines Had Stopped. This Noise Continued As Long As The Vessel Was Moving."* The propeller was 14′-7″ diameter by 14′-3″ pitch with 73 Sq. Ft. blade area, but it is not stated whether it had airfoil or ogival sections. Even if the sections were ogival, we find that when absorbing the full Horsepower at 102 R.P.M., the slip ratio would probably be too low.

We believe it is likely that the propeller on Ship (A) would also operate at a very low slip ratio. Unfortunately the actual powers being used at the R.P.M. at which the other propellers "sang" were not reported, so accurate analyses are not possible in these cases.

Experiments carried out on marine propellers have shown that "similar vibration patterns are produced in air and water"[3], and that "in general, the nodal lines in air and water correspond very closely."

In 1934 Prof. Burrill "found that when vibrated in air, the propellers tested vibrated mainly in modes which were a combination of torsion and flexure i.e., vibrations of torsional-flexural type. The characteristic feature of these vibrations was that while the leading edge of the blade at the outer parts was stationary or relatively so, the trailing edge vibrated vigorously. The propeller blades in question were of markedly skewed mussel shape with wide roots and narrow tips and had airfoil sections at all radii; the end of the maximum thickness line being brought out somewhere forward of the actual tip of the propeller. A very high proportion of these propellers were "singing" propellers and as a result of the tests it was decided to attempt the design of blades having the same general characteristics in so far as blade width, section, etc., were concerned, but having the blade shape adjusted in such a manner that mass balance was secured about a central axis. To achieve this end, the centroids of the sections were arranged to lie on a straight line from root to tip. Propellers designed in this way, when tested with the aid of the electric motor referred to above, showed that so far as

[3] "Marine Propeller Blade Vibrations: Full Scale Tests." Prof. L. C. Burrill M.Sc., Ph. D., N.E.C. Inst., Vol. 62, 1946.

vibrations in air was concerned, this condition had been achieved. That is to say, natural vibrations of the blades in torsion appeared to take place about a more or less central axis and the flexural modes exhibited nodes having their extremities at approximately similar radii. Propellers designed in this way have proved, *in service,* to be quite silent. Other propellers not designed initially in accordance with the above principle, and which "sang" in service were found, upon modification in accordance with this method, to have become silent, and so far as large propellers for merchant ships are concerned, the above method of blade design appears to give entirely satisfactory results."[3]

In the paper from which the foregoing quotation is taken, the author was concerned exclusively with the "bell" aspect of the problem, no consideration being as yet given to the "clapper" or hyrodynamic cause of such vibrations.[3]

In our own case, beginning in 1933 we had marketed many propellers with airfoil sections and a large percentage of them proved to be "singing" propellers. These propellers were made as closely as possible to the shape given in Taylor's Group C.[4] They had Airfoil sections from hub to tip, were of uniform pitch throughout, the blades were of elliptical shape with major axis touching the center line of the shaft, while the point of maximum thickness of each section was at a point ⅜ of its length from the leading edge. All of them had quite thin trailing edges and the patterns were cut to pitch by machine, and then each blade of the propeller was carefully measured and adjusted to the exact correct designed pitch all over. In every case which was reported to "sing", we found the operating slip ratio to be too low, and the blade faces in every case showed signs of erosion. In each of these cases the propeller became silent when the dimensions were changed so that it operated at the proper slip ratio. Not only did it become quiet, but the speed of the vessel was usually increased without increase of R. P. M. This again indicates that the slip may have been too low, and that prior to the alterations there was probably a suction instead of a positive pressure on the blade faces. Your attention is directed to Figs. 2 and 3 which show what seems to be happening when the slip is too low; the streamline flow breaks down and bubbles collapse *on* the blade faces. It is thought that since the marks of erosion show that they collapse *on* the blade, with great violence, we may conclude that these collapsing cavities are the agent exciting the vibration, which, in our experience always accompanies low slip. As shown in Fig. 1, the airfoil blade is quite thin towards the trailing edge as compared with the ogival section and it will flutter more easily on that account. A bronze propeller subject to furious bombardment of collapsing cavities would naturally hum like a bell, and the sound might be termed a "singing" sound in contrast to the "whistling" sound mentioned above as taking place due to the escaping occluded air in way of thick or square trailing edges.

It is quite probable that some propellers could be noisy because of thick edges, and at the same time because of operation at low slip ratio. The former can be easily overcome and in most cases, although annoying, is usually not very harmful. The latter is a warning that should not be neglected since the propeller is vibrating vigorously, and eventually the stern bearing will wear down and the shafting will become fatigued if the condition is allowed to exist.

TO RECAPITULATE

We have found that when operated at low slip ratios, propellers with ogival

[4] "Tests of Model Propellers of Various Blade Sections." Rear Admiral D. W. Taylor, Trans. Soc. N.A.M.E., Vol. No. 38, 1930.

or airfoil sections become eroded on the driving faces of the blades and vibrate to an extent depending on the slip ratio. Also such propellers, when operating at high slip ratio, become eroded on the backs of the blades, but give little or no trouble with regard to vibration. In addition, we find that when operating at low slip ratios the Airfoil propeller, made similar to Taylor's Group (C) sings, while the ogival propeller does not; at high slips neither type sings. The ogival propeller was mass balanced while the airfoil was not. Prof. Burrill's experiments have shown that certain airfoil propellers were changed from "singing" to "silent" by changing the blade shape so that they were mass balanced about a central axis. When not mass balanced they vibrated about the leading edge whereas when mass balanced the vibration at the trailing edge was probably much less violent than before. Mass balance seems to have been equivalent to a stiffening of the trailing edge, for he found such propellers to be silent in service. It is not stated whether any attempt was made to discover if these propellers were operating at the correct slip in service. We believe it possible, indeed quite likely, that if operating at low slip they might still be vibrating although the vibration has become inaudible.

Many of our Airfoil propellers sang in service but became silent immediately after the dimensions had been changed so that they operated at maximum efficiency, and none of them were in mass balance. In such cases the "clapper" of the bell had been removed.

It has been shown by experiment that one type of propeller blade, when caused to vibrate, will do so more easily and more vigorously than another.

By actual use of both, we have found the only ogival or Airfoil propellers to be free from vibration and erosion, are those that operate at exactly the slip which corresponds to maximum efficiency, and also have proven to ourselves, at least, that such propellers do not sing.

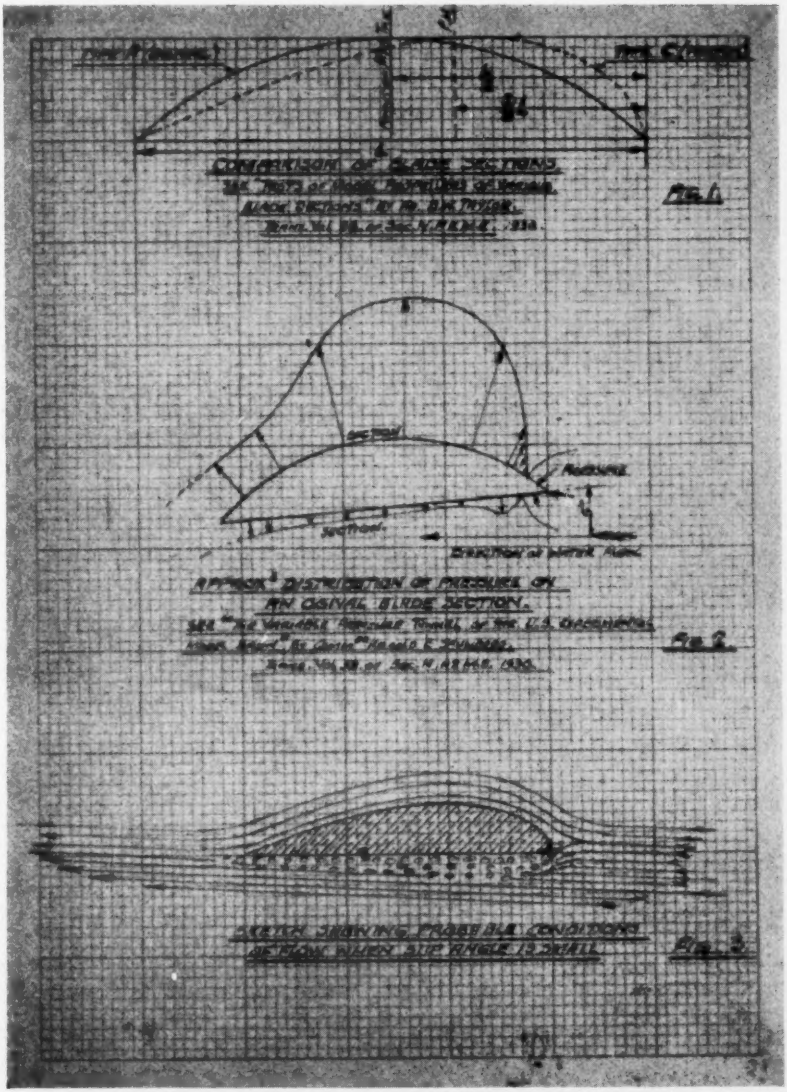
Consequently we believe that if one particular type of section may be shown to be more efficient than another, then it can be used without fear of being noisy, provided the proper dimensions are selected.

A second part of this article, not here reprinted, appeared in the November issue of "Pacific Marine Review." Part II discusses the operation of the LIBERTY type vessels, and suggests that owing to its incorrect dimensions, the vibration responsible for the many shaft failures in these vessels may be coming from the propeller. It is believed that the small stress raisers mentioned by the A. B. S. will assume much greater importance if the propeller is the source of the vibration.

The conclusion is reached that these vessels could be operated at 75 R.P.M. without danger of shaft failure provided the propeller were designed to and actually did operate at the proper slip ratio.

An article "Liberty Ship Tailshaft Failures" was reprinted in the Journal for May 1949.

Fig. 1. Comparison of blade sections.
Fig. 2. Approximate distribution of pressure on an ogival blade section.
Fig. 3. Sketch showing probable conditions of flow when slip angle is small.



THE DESIGN OF REFRIGERATED SHIPS

ACKNOWLEDGMENT

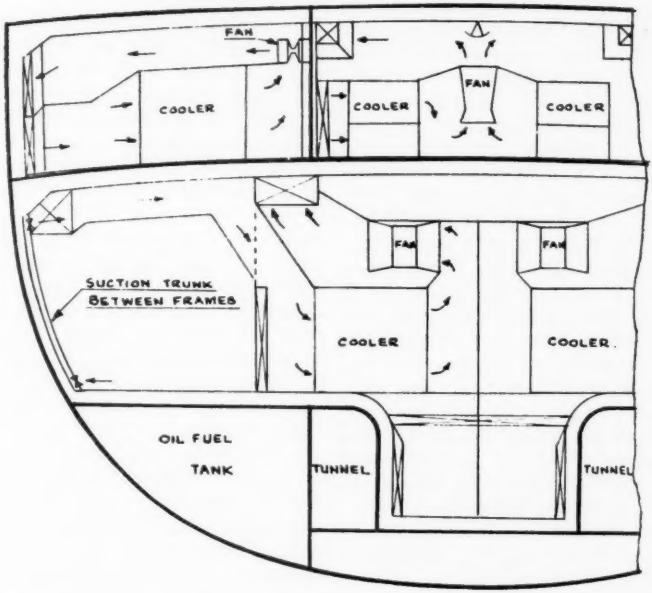
This article by Mr. J. Baird, of the New Zealand Shipping Company, Ltd. and Federal Steam Navigation Company, Ltd. is reprinted from the "Transactions of the Institute of Engineers and Shipbuilders" in Scotland for 1949.

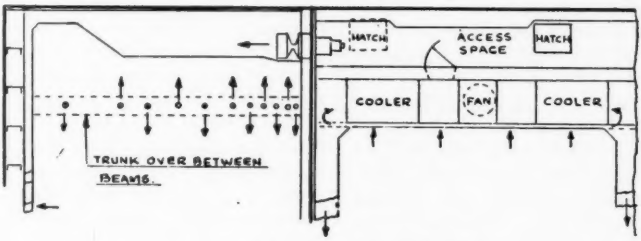
Although small shipments of meat in artificially cooled storage were made from the United States of America before 1879 and certain cargoes were exported from the Argentine, it was in that year the first steamer from Australia to this country carrying a small shipment of frozen meat began what has since become a very large industry. This steamer, the *Strathleven* of about 2,500 tons gross register, was Glasgow owned and was fitted with a refrigerating appliance built by Bell and Coleman of Glasgow. The vessel arrived in this country in the early part of 1880 with 40 tons of beef and mutton which had been frozen on board. The success of this shipment induced New Zealand interests to carry out similar experiments, and the *Dunedin* was equipped in 1882 for this purpose. A number of sailing ships were similarly equipped and successfully carried small cargoes from New Zealand to this country, and one, the barque *Mataura* having been fitted in London with refrigerating machinery actually carried quantities of fish, poultry and game in cold storage from London to New Zealand and delivered her cargo in good order before loading her first homeward cargo of mutton, beef and pork.

The shipments which were made at that time were so successful that a number of steamers were built and fitted with insulation and refrigeration applicances. In the course of the past 70 years the capacity of the steamers has risen from about 100,000 cu. ft. in 1885 to about 250,000 cu. ft. in 1900, and to over 500,000 cu. ft. at the present time. The refrigerated ships are now of such number that probably about 1,000,000, tons of frozen produce is delivered to this country every year.

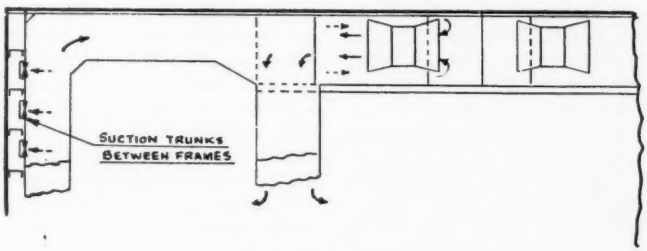
It is not intended to deal in any detail with the methods of the carriage of frozen cargo, as this has been dealt with adequately in earlier papers, but before considering the design of the refrigerated ship it will be well to restate very briefly the system of insulation and refrigeration.

In the modern insulated ship cooled brine is circulated in batteries situated within each cargo space of the ship, and over these batteries air is blown by a fan (Fig. 1). The cooled air is distributed through ducts either vertically or horizontally over the cargo, but more usually a vertical flow is preferred and a suction is provided at or near the floor level of the space through which the warm air is returned to the brine batteries. The spaces are fitted with insulation on all sides to prevent, as far as possible, the ingress of heat to the cargo spaces and cargo. Although the main purpose of the insulation and refrigerating appliances is to cool down the spaces to the carrying temperature and to maintain the low





PLAN AT TWEEN DECK



PLAN AT HOLD

Fig. 1.

temperature of the cargo during the voyage, they can be, and in some cases are, used to reduce the temperature of the cargo from the loading to the carrying temperatures. The cargo, however, is usually received by the ship at temperatures fairly close to the desired carrying temperature and a perfect insulation system should be capable of retaining the cargo at this temperature. Since the present-day insulation is far from perfect, at least in its application, it is necessary during the voyage to maintain mechanical cooling arrangements in order to extract the heat which leaks through the insulation into the cargo spaces. This heat leak is of considerable magnitude. Two papers[1] by Smith and Farmer contain a detailed study of the types and methods of insulating ships' structures and the problem of heat leakage in way of such insulation, and both papers have much of interest to the naval architect.

It is well known that still dry air has the lowest thermal conductivity of materials readily available for insulation and it is this fact that is the important factor in any insulating material. The air may be enclosed in a cellular structure with thin walls, such as granulated cork or pumice, or entrapped in fibrous materials such as glass silk or slag wool, or again the air space may be subdivided by sheet material such as aluminium foil. Although pumice and charcoal were fairly common insulators in the early days, the insulating material is now largely cork, slag wool or glass fibre, which is kept in place against the ship's structure by retaining walls of wood or metal.

GENERAL LAYOUT

Apart from the special arrangements that have to be made in connection with the insulation and refrigeration of the ship, the construction of the refrigerated vessel does not differ fundamentally from normal practice. In the design of any specialized ship it is the owner who understands the necessity for and method of specialization, and it is essential that, when the design is being committted to paper, the shipbuilder should be fully appraised of the various requirements entailed by the specialization. From the requirements of his trade the shipowner will be able to state the speed, deadweight and capacity of the ship, which his advisers will be able to translate into dimensions and form, having constantly in mind the conditions under which the ship is expected to operate. To the shipowner's requirements must be added the requirements of the various operating departments of his business, which have all to be fitted within the main framework. The problem has so many variables that the possible solutions are many and a satisfactory solution must entail compromise and a delicate appreciation of the relative importance of the conflicting claims. It is obvious that the shipowner must have sound and informed technical advice to enable him adequately to present to the shipbuilder the basis from which the final design is to be developed. Much data is now available relating to dimensions, form, form characteristics and power and Dr. G. S. Baker in a paper[2] indicates "signposts" on the way to assess the various values, and the range of vessels dealt with is particularly suited to the modern refrigerated liner.

The stowage rate of a refrigerated cargo is normally very high and will vary between 70 and 110 cu. ft. per ton, so that in the purely refrigerated ship every cubic foot of cargo capacity is vital. For this reason many refrigerated ships are designed with shelter decks and long bridges, but it is questionable whether this is an economical design. Under present conditions most refrigerated vessels trading to this country carry general cargoes on the outward passage, when deadweight may become just as important as capac-

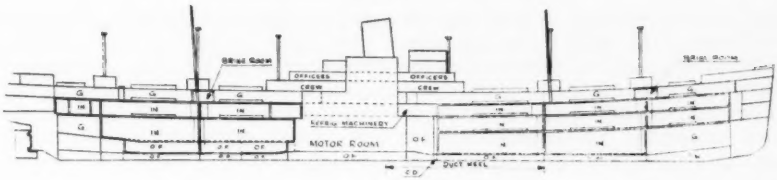


Fig. 2.

ity. It is maintained that if the steel worked into the long bridge is incorporated in the main structure of the ship to increase the depth the total capacity can be maintained, but the deeper ship results in a deeper draught and gain in deadweight for a comparatively small increase in capital cost. With this design loaded stability is improved and the distribution of the cargo spaces permits greater flexibility in loading and greater uniformity in loading and discharge rates as between hatches. The flush deck vessel is free from the discontinuities associated with long bridges. On homeward passages, where the same cargo is carried, the draught of the flush decker will be no greater than that of the shelter deck, long bridge type, and therefore running economy is similar, but in the former additional deadweight is available at a slight reduction in speed—or at a slight increase in capital cost on machinery, if the same speed is desired at the increased deadweight. It is recognized that the gross and net tonnages will be greater with the flush deck ship, and that on this account increased dues may be incurred. In vessels that are designed for the chilled meat trade the depth of the vessel is a deciding factor in the design as the hold and 'tween decks must be of regulated heights for the carriage of their cargoes, and in some chilled meat trades the draught is strictly limited. There is, therefore, less freedom of design than in ships engaged in the Dominion trade, where before the war chilled meat cargoes were of comparatively small amount.

It is not intended to discuss the merits or otherwise of the different types of available propulsive machinery, but it can be accepted that up to the present time a large proportion of the modern refrigerated ships are propelled by internal combustion machinery burning a light type of fuel oil, and that traffic routes and running economy compel the provision of large bunker spaces.

It is important to separate as completely as possible the fuel oil tanks from the refrigerated cargo spaces, as the presence of oil or oil vapor in the cargo spaces will inevitably contaminate the fats of meat and butter. For this reason it is usual to concentrate the fuel oil bunker space in and around the machinery space, and where deep tanks are necessary and are adjacent to refrigerated space, it is the usual practice to fit a cofferdam separating the insulated space from the deep tanks (Fig. 2). It follows, therefore, that the fresh-water tanks are arranged at the ends of the vessel and as the fore end is more liable to suffer from pounding and heavy weather damage the consequent leakage from these tanks will not damage the cargo, or at least the damage will be comparatively small. For reasons that will be given later it is better to keep the bilges clear of suction pipes, and to accommodate these pipes it is usual to fit a duct keel through the forward double bottom oil fuel tanks to take the pipes from the forward spaces. The piping at the after end of the vessel is concentrated in the shaft tunnels in the normal manner. As a point of interest the varying and

seasonal conditions of cargo, together with the large bunker capacity, may induce, in an arrival condition, a very small positive or a negative G.M. and to correct this unsatisfactory condition it is usual to fit the suctions to certain of the oil-fuel and fresh-water tanks with dual valve boxes giving a connection either to the oil-fuel pump or ballast pump, or to the fresh-water pump or ballast pump respectively. To maintain adequate stability the loss of bottom weight caused by the consumption of oil and fresh water is made good by using the tanks alternatively as salt-water ballast tanks.

In ships engaged in the Dominion trade a certain amount of general cargo space is always provided for the carriage of wool, tinned goods, etc., and to facilitate loading and refrigeration arrangements generally, the general cargo space usually takes the form of an open shelter 'tween deck. Owing to their shape the forward and after holds are uneconomical to insulate and are less satisfactory as refrigerated spaces, and as these holds are often in demand for dirtier general cargoes outwards and homewards it will be found, in many instances, that these holds are not refrigerated, although this is not a general rule.

These considerations decide the arrangements of the vessel generally, but the necessity of carrying general cargoes on an outward voyage means that serious consideration must be given to this aspect of the problem, and the size of the cargo hatches are mainly dictated by outward voyage considerations, while the spacing of the hatch webs is arranged to suit the fitting of insulated hatch plugs and the special requirements for the loading of insulated cargo. There are no peculiarities about the cargo gear, which is arranged to suit each company's normal methods, but access must be provided between hatches from the weather deck to the fanrooms and refrigerating coolers in the refrigerated spaces, and as this access is necessary at sea it should be adequately protected from the weather and is usually fitted in winch or mast houses. The crew accommodation is, of course, arranged to suit individual requirements, but it is better arranged above a general cargo 'tween deck as considerable dampness and discomfort is likely to arise where the accommodation is situated immediately over refrigerated spaces, due to condensation in the warm living spaces in way of boundary bulkheads and decks separating them from the cooled spaces, and it is difficult, even at heavy expense, to obviate these troubles.

CONSTRUCTION

The depth of framing is mainly regulated by the depth of the holds, and as the framing is entirely covered with insulation, this framing depth is an important factor in the resulting refrigerated capacity of any space. The tendency has been to fit shallow sections of channel type with reverses as necessary to minimize the depth of the framing. The alternative to this is to reduce the height of the 'tween decks or holds but, apart from the chilled meat trade, these are dictated by the requirements of general cargo. While, of course, equivalent strength is obtained in the shallow frame girder, care is necessary that stiffness of the girder is not sacrificed by the fitting of a too shallow section. It is pointed out in Smith and Farmer's earlier paper[1] that a major source of heat leakage into any space is through the frames and certain deck beams, and that this heat leakage increases with the width of the inner flange of the frame or the flange of the reverse bar and increases at a very high rate. From the point of view therefore of efficient refrigeration it would be preferable to fit ordinary angle or bulb angle framing but from the point of view of earning capacity, the resulting necessary

depth of this type of framing is extremely wasteful. A frame, therefore, is usually of the built-up or channel type and particular care must be taken with the insulation of these inner flanges. Similar procedure is necessary in way of bulkhead stiffeners and deck beams although as these items are mainly part of dividing decks or bulkheads between cooled spaces they have not the same importance as the ship's side framing or top deck beams. For efficient insulation it is better to arrange the deck beams of a standard depth in spite of the varying spans towards the ends of the vessel. From the point of view of purely chilled meat cargoes, shallow girders with closely spaced pillars are probably the best arrangement, but here again the requirements of general cargo demand large clear holds, and it is more usual to find widely spaced pillars in association with heavy girders of restricted depth.

Reference has already been made to the seriousness of oil leakage, and with the introduction of Diesel machinery this leakage caused considerable trouble in way of double bottom oil-fuel tanks, and more especially at the bilges in way of refrigerated holds. With the earlier form of flanged margin plate and overlapping gusset plates it was almost impossible to obviate this oil leakage through the rivet connecting the gusset plate to the margin plate. A later arrangement was to carry the tank top plating flat out over the bilge, thus incorporating the gusset plate with the tank top plating, the margin plate being fitted to this extension with a hooked angle bar which permitted better riveting and the caulking of the heel and toe of the vertical flange of the tank top margin bar in way of the bilge; this certainly gave much improved results. Nowadays the whole of this detail can be a welded construction, which appears to be the only satisfactory answer to the question of oil leakage in way of refrigerated cargo hold bilges. It is also good practice to weld all seams and butts of the tank top in way of double bottom oil-fuel tanks. There is no doubt that cofferdams were necessary with riveted construction as it was impossible to prevent oil leaks through the allegedly oil-tight bulkhead. It would appear, however, that with the development of welding technique it may be possible to omit these cofferdams with advantage to the carrying capacity of the ship. It should be pointed out that all access manholes from refrigerated spaces to double bottom and deep oil-fuel tanks should be of double cover type to minimize oil leakage in way of these manholes.

In the chilled meat trade from the Dominions in pre-war days the duration of the voyage necessitated the meat being carried in an atmosphere with a 10 per cent concentration of CO_2, and to maintain this gas concentration it is essential that the chilled meat lockers should be gastight. For this reason it is usual to fit the lockers on the port and starboard sides of the cargo hatches and to minimize obstruction of the insulated spaces it is also usual to incorporate the longitudinal divisional bulkheads forming the inner boundaries of these lockers with the pillaring and girdering of the ship. Special arrangements are made in way of beams and frames where they pass through bulkheads and decks to maintain gastightness by the fitting of adequate stoppers.

With the introduction and more general use of welding it is of course easier to obtain a good gastight locker, but if proper attention is not paid to the design of the longitudinal bulkheads, and more especially to the details of well-rounded corners at door openings and to bulkhead compensation in way of these openings, eventual trouble, both structural and in gastightness, is certain. As the surfaces of

the bulkhead are sheathed in insulation, the results of bad design or faulty workmanship may be dire before the cause is suspected. This applies to any part of the structure in way of insulation and every effort should be made to ensure that the steelwork and piping which will eventually be buried in insulation is satisfactory. Any structural repair, even of a trivial nature, can be very costly as the result of the necessary removal and refitting of refrigeration equipment and insulation in way of the damage.

The fitting of chilled meat lockers, and the requirement imposed by the simultaneous carriage of different types of refrigerated cargo that all main spaces should be practically isolated from each other, means that the decks are everywhere in close contact with the shell, and the deck is therefore a major source of heat leakage through the shell into the insulated spaces. In chilled meat ships on the South American trade where the shorter duration of the voyage does not require CO_2, where similar cargoes are carried at similar temperatures in adjacent spaces, and where a larger number of lower platform decks may be fitted, it is usual not to connect these lower decks to the shell, thereby minimizing the heat leakage from the shell through these decks. Where it is proposed to carry chilled meat hung from beams with the possibility of deck cargo carried above the beams, the usual increases are made to the beams, girders and pillars to take account of additional loading on the deck.

The position selected for the refrigeration machinery should be such that a good solid foundation is obtained, otherwise annoying vibration troubles are liable to arise when the machine is in operation. In the earlier days of refrigeration, when the holds were cooled by brine grids without forced air circulation, it was usual to take the supply and return pipes for the brine grids in all spaces direct from the refrigeration engine room, this room usually being situated somewhere adjacent to the main engine room. This entailed the fitting of a very large number of pipes through the midship 'tween decks, with the result that a large part of the deck plating on the second and third decks was almost completely cut away to afford passage to the pipes. The fact that no compensation was provided and that the pierced deck plate was often the stringer plate appeared of little consequence. Watertight bulkheads were similarly cut, but as each pipe had to be fitted with a watertight gland the final effect was bewildering. The pipes were carried along the ship's side, where in the event of even a slight shell damage the consequent repair necessitated the very costly removal and refitting of brine pipes and heavy insulation. To minimize this many of these pipes were later carried under the deck, but owing to the concentration of low temperature brine it was difficult to insulate these pipes adequately and this caused a certain amount of trouble due to condensation on the casing insulation. To obviate the severe destruction of deck and bulkhead material, and to facilitate refrigeration arrangements generally, brine control rooms are now fitted remote from the main refrigerating engine room, the brine being delivered to these control rooms from the main room through a few pipes of large diameter, and the necessary distribution is then made from the brine control rooms to the coolers in the cargo spaces.

INSTALLATION OF REFRIGERATING EQUIPMENT

Fig. 1 illustrates the modern method of circulating air in the holds and 'tween decks, and it will be noted that in order to economize space certain of the air supply and exhaust trunks are fitted where they can be economically arranged between frames and between deck beams. Compared with the depth

of insulation in way of the inner surfaces of frames, beams and stiffeners there is a redundancy of insulation between these members, but this modern system of fitting the circulating trunks goes some way towards overcoming this redundancy, and in the case of the hold suction trunks goes one step further. These metal trunks are supported from the ship's side frames in close thermal contact and the return air to the cooler passing through the trunks conducts a certain amount of the heat from the frames and therefore minimizes the amount of heat leakage at the inner surface of the frame. This does not of course reduce the load on the refrigerating plant but it does reduce the amount of heat actually passing into the cargo space at a point of maximum heat leakage. It will be observed that the principle of cooling is to circulate the cold air from the fans through the delivery trunks, over the cargo and through the suction trunks, over the coolers back to the fans. Change-air pipes led from the weather deck are provided in way of each fan so that fresh air can be introduced into the space as carriage conditions demand. Direct access is provided to all coolers and fans through the access spaces and access hatches in each deck so that fans and coolers can be under direct observation during the voyage.

A modern system of insulation is illustrated in Fig. 3 which consists essentially of a sheet steel or plywood retaining lining held in place by rolled mild steel sections with fixing nuts and bolts arranged in special clips attached to the framing members of the ship. In this system the bolts and nuts are insulated with fibre washers from the clip and it is claimed that leakage of heat by conduction through the bolts is almost entirely eliminated, or is at least much minimized as compared with the earlier method of welding these bolts direct to the ship's structure. It will also be observed that the inner flanges

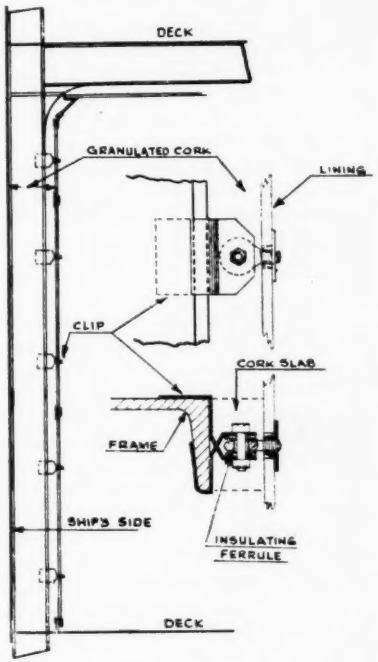


Fig. 3.

of the framing members are more efficiently insulated with cork slabs and that very little wood grounding is required. In the earlier insulation system the lining was formed largely by tongued and grooved pine boards which were nailed to wood grounds bolted to the frames and beams, and there is no doubt that with this system the minimum of insulation and the maximum of heat leakage coincided. The tank top insulation usually consists of a lower lining of tongued and grooved pine boarding laid on grounds to form an air space above the tank top plating. Wood bearers 6-7 in. in depth are laid on this lower lining with the intervening space filled with granulated cork and the whole covered by two layers of tongued and grooved lining

nailed to the bearers. Alternative systems have been used where slab cork has been laid direct on the tank top plating and covered with a reinforced bituminous coating, and while this makes a very good insulated floor, in the event of tank top leakage it is exceedingly difficult to discover or trace this leakage until extensive damage has been done to a large area of the tank top insulation. This system is also liable to heavy damage from general cargo.

Reference has been made to heat leakage through decks where these are connected to the shell plating; this leakage can be considerable in the stringer plate and adjacent strake. The underside of the deck is, of course, insulated beyond the depth of the deck beams but in many instances the upper surface of the deck, even when it forms the floor of an insulated upper 'tween deck, is left uninsulated. About 2 ft. of the deck surface adjacent to the shell plating is protected by the ship side lining and cold air screen and, although this is the position of maximum heat leakage, the leakage for some feet inboard of the screen is very considerable. It is usual to accept this leakage where general cargo might rapidly destroy any deck covering, but in way of chilled meat lockers, where temperatures must be maintained within fine limits, the upper surface of the lower deck is insulated with slab cork and a protective covering. The insulating medium most usually employed is slab or granulated cork, although large amounts of glass wool and slag wool are at present being used. Experiments have been made with alternative types of insulation and much valuable information is given by E. Griffiths[3] and M. J. Hickman[4]. While there will undoubtedly be developments in this field, so far there has been little departure from the insulating materials used during the past 20 years. Whatever system is used it is essential that the linings containing the insulating medium should be as airtight as possible, especially in view of the modern system of cooling by air circulation.

The refrigeration process and the nature of the cargoes carried require the fitting of specialized drainage systems to each space (Fig. 4). Scuppers from all 'tween decks and from the hold tank top insulation are, of course, a classification requirement. Similar scuppers are also required from chilled meat lockers and at one time it was the practice to fit these scuppers with solid screwed plugs in order to render the lockers completely gastight when carrying chilled meat on a long voyage. As this is in direct conflict with the normal scupper requirements, the fitting, of these plugs is now forbidden and it is presumed that gastightness must depend upon the efficiency of the brine seal in the scupper pipes. The process of refrigeration and the nature of the cargo causes the water vapor in the return air to condense on the cold brine piping of the coolers and to ensure continued efficient working of the coolers the resulting snow and ice has to be thawed off at intervals. Adequate drainage must therefore be arranged in way of all coolers and cooler spaces and from any adjacent working spaces such as access spaces where, owing to the proximity of such spaces to frozen spaces, the condensation and consequent drainage may be heavy. Because of the possible variations in the type of cargo carried, the drainage from each space is entirely independent of any other space, and to ensure this isolation all scupper drains terminating in the bilges are fitted with brine-sealed U-bends with clack valves. The leads of these pipes require to be carefully considered and accurately fitted to ensure that they are well insulated and protected from the possibility of freezing and damage. This applies also to the normal sounding pipes and air pipes from double

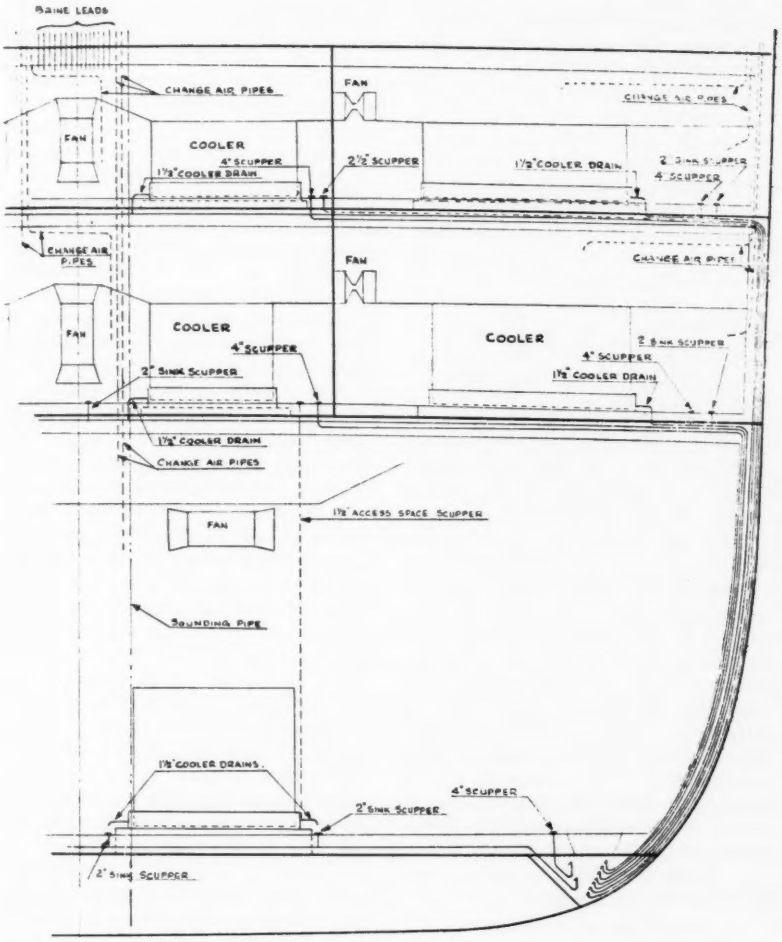


Fig. 4.

bottom tanks which may pass through insulated spaces, and in fresh-water tanks care should always be taken that when tanks are filled no head of water should be standing in such pipes. If water is left in the pipes it may freeze and fracture the pipe, and on a subsequent filling of the tanks extensive water damage may be done to valuable cargo before any damage to the buried pipe is suspected. It is also desirable wherever possible to keep the pipes clear of hold or 'tween deck brine coolers to facilitate repairs and minimize damage. Thermometer tubes extending from the weather deck into

each space, with anything up to 6 tubes per space, are normally fitted. The tubes permit thermometers to be lowered into predetermined points of each space. Where the steel tubes pass through the steel decks they are insulated from the decks by wooden ferrules. Modern practice is tending to depart from this system of taking cargo temperatures and electric or liquid distance thermometers recording in the control room are taking their place.

The carriage of fruit cargoes entails a careful watch on the CO_2 of the refrigerated spaces as the ripening fruit exhaling this gas may suffer irreparable damage unless the concentration of CO_2 in the hold is controlled. Under modern conditions the control is affected by the change-air pipes already referred to, but in the earlier vessels special extractor fans were supplied for ridding the space of the CO_2, the fans being fitted to the top of the thermometer pipes, which acted as supply and suction pipes. It is unnecessary to fit any natural ventilation to the refrigerated spaces as with the modern system of refrigeration the fans and change-air pipes can be utilized to ventilate general cargoes and can give a more controlled ventilation than the natural system. It will be appreciated, therefore, that the piping system of the refrigerated ship is extensive and, to be satisfactory in operation, requires careful designing and more careful installing.

PROBLEMS OF OPERATION

A few of the problems which arise in connection with the operation of these ships may not be without interest, and may have a wider application. Conditions of the trade may require large bunkers and one bunkering port, and the seasonal nature of the cargoes may be such that satisfactory stability in an arrival condition is only possible with the use of alternative water ballast in oil-fuel tanks. This, of course, entails liquid, either oil or water, in a large number of tanks and the available cargo loading may impose a comparatively small G.M. In a few instances the G.M. as calculated from the technical particulars supplied to the ship has been stated not to be in accord with the apparent G.M. of the ship. On careful checking the discrepancy has not been apparent although the necessary allowance was made for tanks known to be slack. Experiment has shown that the G.M. in loaded condition was less than that calculated on the basis of the original inclining experiment although all tanks containing liquid were apparently full. On subsequent manipulation of the tanks and of the vessel it was found in the tanks which appeared to be entirely full that, either owing to the position of air pipes or to peculiarities of construction, there was in fact an air pocket, so that the allowance for free surface actually made in the calculations was proved to be far from adequate. Attention is therefore drawn to the necessity for the proper positioning of the air pipes and to the provision of adequate air escapes, or alternatively for some arbitrary allowance being made to take account of the practical impossibility of ensuring that all tanks are indeed hard pressed. It is, of course, only in the nearly upright position that the apparent loss of stability is noticeable and when the larger double bottom tanks are in use, but with a necessarily small G.M. the tendency to flop can be disconcerting where the cause is not properly understood. In this connection the question of the virtual center of gravity of a hanging cargo such as chilled meat calls for consideration. It is the common practice to take the vertical center of this cargo as being applied at the hook upon which the cargo is hung, but in the case of a chilled-meat vessel it is questionable whether this does not impose a serious restriction on the design of the ship. The chilled meat is carried in lockers

of such size that close stowage of the carcases should be possible and movement very limited.

Many comments have recently been made on the length of time required, as compared with pre-war conditions, to turn ships round in Dominion ports, and the waste of material, time and effort is indeed to be deplored. A further disadvantage of these long delays is becoming apparent in that the fouling of bottom shell is now of such extent as to reduce homeward speeds by as much as a knot as compared with outward speed under equivalent conditions. While it is to be regretted that the fruits of much research and the time and labor expended on providing better ships giving better performances are thus thrown away, it does appear that intensive research into the problem of roughness of immersed surface and fouling is still necessary. It is doubtful whether the effectiveness of available anti-fouling compositions is worth the cost and indeed the repeated application of these compositions over a surface imperfectly cleaned and protected by anti-corrosive paints of doubtful value can eventually do more harm than good. The problem is economic as well as scientific but it is suggested that it is of real practical importance and complementary to the more academic researches undertaken to improve the propulsive efficiency.

CONCLUSION

The paper contains no results of original research and practically no data but gives the result of experience gained over some years with this type of vessel. It is written for the information of those whose work may bring them into contact with refrigerated ships and in the hope that it will create a fuller appreciation of the problems and the attempted solutions involved in their design.

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MEMBERSHIP CHANGES

NEW MEMBERS

It has been the privilege of the Society to accept the following new members since the publication of the list in the November, 1949, issue of the JOURNAL.

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DEATHS 1949

The Society has learned with regret of the deaths of the following members:

HONORARY

Schmidt, Henry F., Prize Essayist 1927

NAVAL

Lis, Stanley J., Lieutenant, U.S.N.R.

CIVIL

Freney, James J.
Jennings, Aaron J.
Morse, Charles Hosmer, III
Smith, J. E.

ASSOCIATE

Kerlin, Ward Dix

OTHER LOSSES

During 1949 resignations accepted from members and members dropped in accordance with the By-Laws resulted in losses as follows:

Naval	121
Civil	30
Associate	32
Total	183

MEMBERSHIP LIST

A new and complete list of members will be published in the near future. All members of record when the 1950 bills were mailed were furnished with a short form for furnishing information to be printed in the list. The list which will be published will reflect the accuracy of our records as brought up to date by these forms. All hands are urged to complete and mail their forms.

MEMBER'S ADDRESSES

All members are urged to check the address under which they received the last mail from the Society and to drop a penny post card in the mail to us advising of any change in address which is in order.

ASSOCIATION NOTES

Original Articles

The editor of the JOURNAL is most anxious to obtain manuscripts of original articles on subjects of interest to naval engineers. Any manuscripts accepted for publication becomes the property of the Society which copyrights it upon publication. Authors are paid from $50.00 to $150.00 depending upon length, interest and professional value.

The rules for manuscripts are as simple as we can make them.

1. They must be legible (typewritten, double-spaced preferred) since no proof is submitted to authors for correction prior to printing.

2. Single copy only is required.

3. Mathematical formulae used must be set up, preferably by hand printing, so that there can be no question as to symbols, subscripts and exponents.

4. Any drawing submitted must be black on white. A cloth or paper tracing is acceptable but not required.

5. Photographs may be negatives, but glossy prints are acceptable.

6. Include on a separate page a short biographical sketch(es) of the author(s). 50 to 100 words for each author is desired.

Manuscripts should be mailed addressed to:

Secretary-Treasurer
American Society of Naval Engineers
Bureau of Ships, Navy Department
Washington 25, D. C.

Manuscripts accepted will not be returned unless specifically requested by the author. If returned, they will be in the condition which has resulted from the work of the printer and the engraver. Immediately following publication, the author is furnished 10 reprint copies of his article free of charge. Additional copies may be purchased from the Society if the request is received 30 days prior to the publication date which is the 25th of the issue month. Estimate of cost of additional reprints, which will vary with the nature of the article and the number of copies ordered, will be furnished on request as soon as possible after the article is set up.

Manuscripts not accepted will be returned, postpaid, by the Society.

Manuscripts which are accepted will be published in the earliest JOURNAL which has not yet been closed (60 days before publication) and for which insufficient material is already on hand.

SUBJECT MATTER AND AUTHORS

To assist the editor in programming future issues, the help of all members is solicited. To make it easy, the last page in this issue is readily detachable as you will find. This page has blanks for two entries.

(*a*) What subject would you, as a member, like to see covered by an article in the JOURNAL.

and

(*b*) Who do you consider best qualified to prepare such an article authoritatively, and what is his address. (if you know).

Any of these forms which are filled in and mailed to the Society will be received with thanks and the editor will follow up to get the suggested articles prepared.

PHOTOGRAPHS

Photographs of current or historical interest to readers of the JOURNAL are desired. Any which are accepted by the Society will be purchased by the Society at a standard price of $5.00 each. Such purchase *will not* include any copyright by the Society, but the contributor must hold the Society free from any charge of violation of any previous copyright.

NOTICE OF DEATHS

The Society has no satisfactory machinery for obtaining notice of deaths of members. It is particularly desired that we receive such notice upon the death of any past officer, past member of the Council or member of more than twenty years' standing with photographs and short obituaries. It will be appreciated greatly if any member who learns of the death of a member will advise the Secretary-Treasurer.

SOCIETY LAPEL BUTTON

Shown below is an illustration of the lapel button of the Society. It is believed that it will be conceded that this is a very fine dignified insignia. It is one-half inch in diameter.

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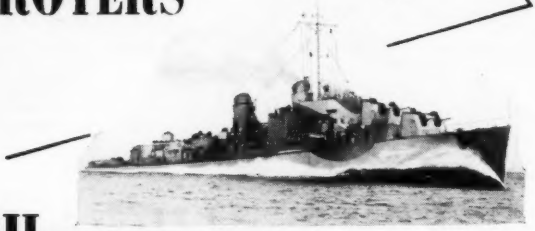

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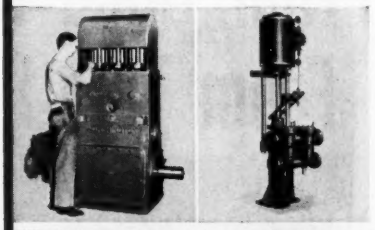

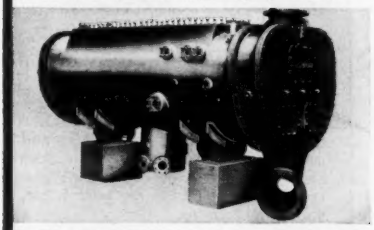

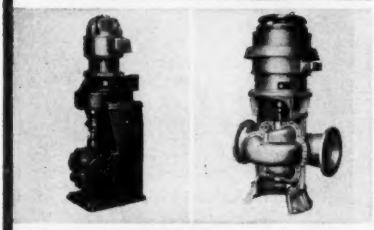

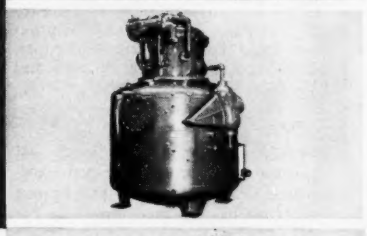

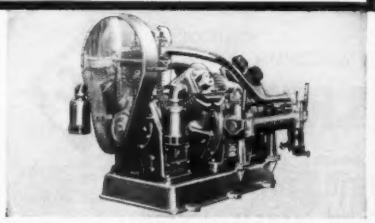

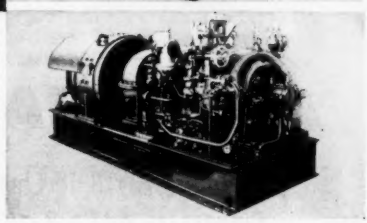

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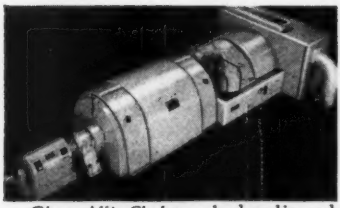

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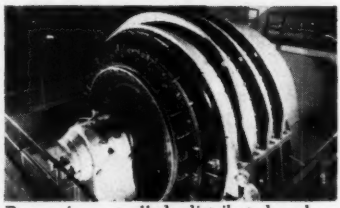

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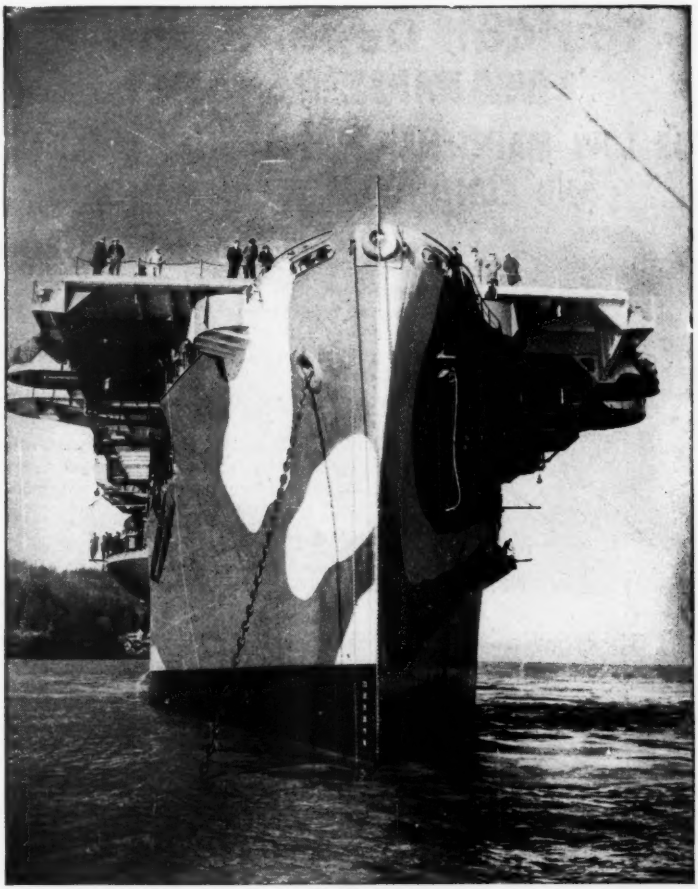

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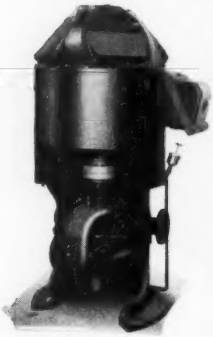

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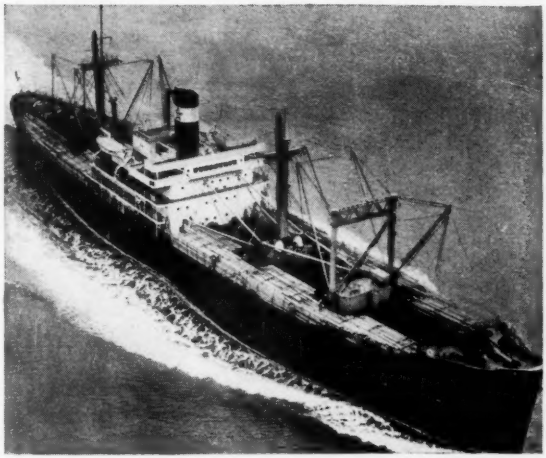

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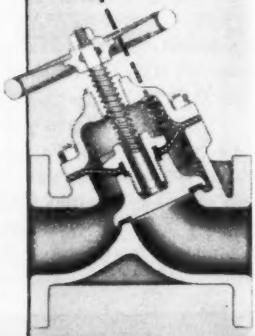

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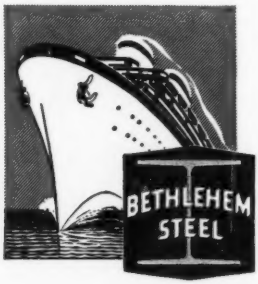

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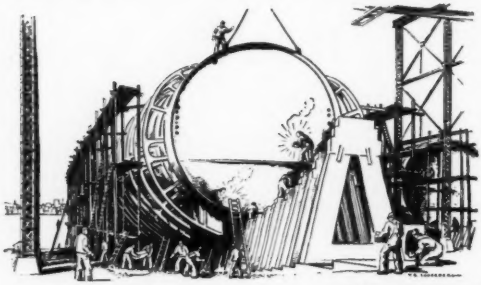

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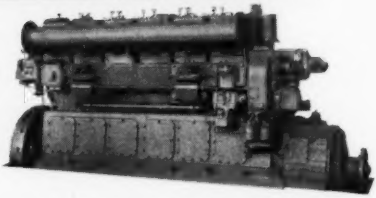

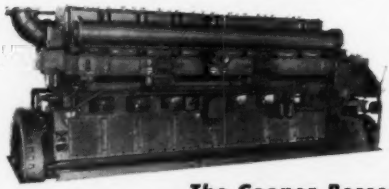

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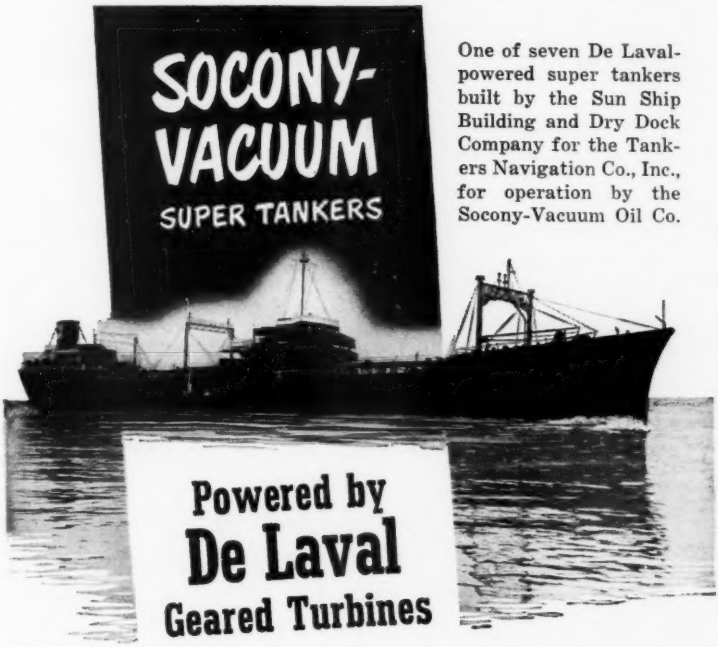

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